OCCURRENCE OF PERCHLORATE AND METHYL TERTIARY BUTYL ETHER (MTBE) IN GROUNDWATER OF THE AMERICAN WATER SYSTEM

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EXECUTIVE SUMMARY

The occurrence of perchlorate and methyl tertiary butyl ether (MTBE) in groundwater supplies has generated a lot of concern. This report provides a literature review of both of these compounds addressing their chemical properties, occurrence, health effects, treatment, and regulatory status and summarizes monitoring data from groundwater sources in the American Water System.

Available literature indicate perchlorate can occur in levels of up to 165 μg/L in surface waters and up to 280 μg/L in some California ground waters. However, of the total 386 samples collected and analyzed from the American Water Works Service Company's ground water sources (from sixteen states and from diverse locations), only ten tested positive (<3%) indicating that perchlorate contamination is a localized problem for water sources located near ammunition factories, defense establishments and perchlorate manufacturing plants. The perchlorate concentrations ranged from <4 to 6 μg/L, well within the guideline value of 18 μg/L, suggested by California Department of Health. Treatment alternatives exist for decontamination of wastewater containing high concentration of perchlorate, but no effective techniques are presently available for removing low levels of perchlorate from drinking water sources.

A total of 2120 samples representing 450 wells (raw and treated) were tested from 16 states during 1997 for methyl tertiary butyl ether (MTBE). Only 44 samples (~2%) tested positive for MTBE, representing 17 wells (~ 4%), and the highest concentration (8.0 μg/L) was well below the EPA health advisory recommendation of 20-40 μg/L. Of these 44 samples, 22 were raw water, 21 treated water and one was from a distribution system. The main sources of MTBE contamination are underground storage tanks, pipelines, and spills. As of the end of 1997, there have been over 340,000 confirmed releases from underground storage tanks in the U.S. MTBE and other gasoline constituents have also been detected in several lakes and reservoirs across the country, with the source of MTBE thought to be release from recreational boating. Preliminary results have indicated that GAC filtration and air stripping remove MTBE in the range of 27-55%, with the removal efficiency a function of the initial MTBE concentration. The application of these technologies as a combination treatment can be expected to enhance the removal of MTBE from contaminated sources.

Overall, while the study does detect low levels of perchlorate and MTBE in some groundwater sources, the levels do not pose a health or aesthetic risk. The report does highlight the need for American subsidiaries to remain vigilant with regard to potential sources of contamination within well fields, especially with underground storage tanks, landfills, and industrial pollutants. Not all American Systems have formal wellhead protection programs in place. Such guidelines should include coordination with State program, monitoring of activities on Company-owned property surrounding the wellhead, development of local wellhead protection ordinances, and an assessment of the need to acquire additional property around the well so as to exercise control of activity within the area of influence of the well.

CONCLUSIONS AND RECOMMENDATIONS - PERCHLORATE

- Perchlorate is not a regulated compound under Safe Drinking Water Act, therefore currently there are limited data available regarding its occurrence. No comprehensive occurrence data is available for surface waters. A seasonal variation and occurrence data for both surface and ground source waters is needed since perchlorate's mobility in aqueous phase is temperature dependant.

- Recent detection of perchlorate in several surface waters and ground water wells used to supply drinking water has created an unforseen water contamination crisis in the Western states, although problems are likely to emerge at other sites where perchlorate is used. Subsequent monitoring of 232 groundwater wells in California indicated perchlorate was in 69 wells (30%) and at concentrations above the action level in 20 wells (9%) (CDHS, 1997; AWWARF 1997). Samples taken from the Las Vegas Wash, which feeds Lake Mead and then the Colorado River, contained 1,500 to 1,680 μg/L (Urbansky 1997). The Los Angeles Metropolitan Water District measured 8 ppb in water at its intake in Lake Mead, and the Southern Nevada Water Authority found 11 ppb in its tap water.

- Of the total 386 samples collected and analyzed from American Water Works Service Company's ground water sources from several states and a diverse set of locations, only ten tested positive for perchlorate. The perchlorate concentrations ranged from <4 to 6 μg/L, well within the guideline value of 18 μg/L, suggested by California Department of Health.

- The presence of perchlorate in drinking water sources is not a widespread problem but rather a localized problem. The data indicates it is associated with ordnance facilities and perchlorate manufacturing facilities. Perchlorate is used in solid rocket propellants, and has been found in areas where aerospace materials such as rocket fuel, fireworks, and munitions were manufactured and tested.

- It is imperative that control measures be in place to further stop the spread of contamination. Source control of perchlorate using removal and disposal of contaminated soil/water, incineration, phytoremediation, and constructed wetlands is a long lasting cost-effective solution to perchlorate intrusion into drinking water sources.

- Treatment methods effective for the removal of other pollutants are ineffective in the treatment and removal of perchlorate from the water supply. As discoveries of perchlorate grow in number, the urgency to discover a safe and efficient system of removal is imperative. The need for treatability studies to address the feasibility of perchlorate treatment at high flow rates and low concentrations exist.

- Recent improvements in analytical procedures allow identification of low concentrations of perchlorate in groundwater and surface water supplies. The current detection limit for this compound using ion chromatography method is 4 μg/L.

- A better understanding of perchlorate toxicity may help refine risk assessment and arrive a cleanup goal for drinking water sources that is both cost effective and provides an adequate margin of safety for all potential users.

CONCLUSIONS AND RECOMMENDATIONS FOR MTBE

■ There is paucity of information related to the removal of MTBE from drinking water sources. Technologies needed to be studied include oxidation, air stripping, activated carbon fibers, and bio-filtration. Air stripping is known to work but information on the efficacy of air stripping in combination with other processes such as GAC or bio-filtration is required.

■ A total of 2120 samples representing 450 wells (raw and treated) were tested from 16 states during 1997 for methyl tertiary butyl ether (MTBE). Only 44 samples (~2%) tested positive for MTBE, representing 17 wells (~ 4%), and the highest concentration (8.0 μg/L) was well below the EPA health advisory recommendation of 20-40 μg/L.

■ MTBE contamination of groundwater should be considered to be a potentially nationwide problem and not just a localized or a coastal problem. Over a million USTs exist in the United States and many are in bad condition and the potential to cause a widespread groundwater contamination problem is present.

■ The concentration of MTBE in groundwater sources may be expected to increase in the years to come as use of reformulated gasoline increases. It is imperative to monitor MTBE concentrations on a regular basis and improvements of treatment plants using ground waters should consider MTBE control strategies.

■ To maximize MTBE removal from ground water sources, an optimum air-to-water ratio should be used and an effective carbon contact time established. For plants where air stripping alone is not effective, use of GAC or carbon fibers in combination with stripping should be considered.

■ The systems currently using GAC are not designed for MTBE removal. An optimization study should be performed to enhance the removal of MTBE along with other SOCs. The GAC contact time and the type of GAC is crucial to effectively remove SOCs and this should be kept in mind when choosing a new or replacing existing GAC filtration systems.

■ For MTBE-contaminated source waters where there is a chronic problem with taste and odor compounds, VOCs, or iron or manganese problems, the use of ozone should be evaluated as a cost-effective multiplicative strategy. Bench or pilot-scale studies should be performed to evaluate the decomposition of MTBE by ozone. A combination of ozone oxidation and biological filtration should be evaluated as a cost-effective integrated system to remove MTBE and other organic contaminants

- Biodegradation rates and pathways need to be studied to understand the fate of MTBE and its products, and to design cost-effective control strategies.

- Any shallow ground water sources should be phased out or properly treated to reduce the potential for contamination.

- Trip blanks should be included in sample kits for MTBE analysis to evaluate the impact of sample contamination by gasoline fumes at the time of sampling.

OCCURRENCE OF PERCHLORATE ION [ClO4] IN DRINKING WATER SOURCES

OCCURRENCE OF PERCHLORATE ION [ClO$_4^-$] IN DRINKING WATER SOURCES

ABSTRACT

The recent discovery of perchlorate ion in both surface and ground drinking water sources is cause for concern. Available literature indicate perchlorate levels of up to 165 μg/L in surface waters and up to 280 μg/L in California ground waters. However, of the total 386 samples collected and analyzed from the American Water System's ground water sources (from sixteen states and from diverse locations), only ten tested positive (<3%) indicating that perchlorate contamination is a localized problem for water sources located near ammunition factories, defense establishments and perchlorate manufacturing plants. The perchlorate concentrations ranged from <4 to 6 μg/L, well within the guideline value of 18 μg/L, suggested by California Department of Health. Although treatment alternatives exist for decontamination of wastewater containing high concentration of perchlorate, no effective techniques are presently available for removing low levels of perchlorate from drinking water sources. This article summarizes existing data of perchlorate occurrence and potential removal technologies for controlling perchlorate from drinking water sources.

Key Words - perchlorate, ground water, occurrence

INTRODUCTION

Ammonium perchlorate is used in solid rocket propellants, and has been found in drinking water wells in areas where aerospace munitions development and manufacturing has occurred. Contamination can also arise as a result of discharging wastewater from chemical industries which manufacture ammonium perchlorate. Perchlorate salts have a wide variety of applications, including uses in nuclear reactors, electronic tubes, as additives in lubricating oils, in the manufacture of pyrotechnics and explosives, in tanning and finishing leathers, as a mordant for fabrics and dyes, in electroplating, aluminum refining, and rubber manufacture; and in the production of paints and enamels. It was also once used in the chrome plating industry. Perchlorate may also enter the environment from industrial and municipal wastewater treatment plant discharges, or spills. Perchlorate is also used on a large scale in the use of automotive air bags.

Solid rocket fuel disposal inventories are growing at a significant rate as systems reach the

end of their service life and as treaties remove motors for disposal. The current disposal method for these motors is open burning or open detonation which is becoming increasingly difficult to perform under intense public and regulatory pressure. Present large solid rocket motor disposal inventory shows 55 million pounds of propellant is currently awaiting disposal. By the year 2005, it is expected that this amount will grow to over 164 million pounds (Armstrong Lab, 1997). A significant portion of this inventory contains the oxidizer, ammonium perchlorate, which can now be reclaimed and recycled into new motor propellants. It is a contaminant in groundwater and surface waters in 14 states (Renner, 1998).

Ammonium perchlorate is the oxidizer and primary ingredient in solid propellant for rocket motors. The accepted method for removal and recovery of propellant from rocket motors is high-pressure water washout. This method generates large amounts of aqueous solution containing ammonium perchlorate. Ammonium perchlorate can be recovered from aqueous solutions; however it is cost-prohibitive to recover all the ammonium perchlorate. The resulting waste stream contains low concentrations of ammonium perchlorate and must be treated. The U. S. Environmental Protection Agency (EPA) has issued a provisional reference dose for ammonium perchlorate that could restrict discharge to less than 5 μg/L and have severe impact on defense propulsion contractors (CDHS, 1997). The Minuteman III propulsion recovery program will remove over 35 million pounds of propellant from first- and second-stage rocket motors as part of the motor case reclamation process (Armstrong Lab, 1997). This means that water utilities may be confronted with large quantities of aqueous waste containing ammonium perchlorate.

Testing for perchlorate has been done throughout California and Nevada at facilities considered at risk of being impacted. In addition, EPA and other groups are considering nationwide surveys. This contaminant has the potential of becoming a national problem to water supplies. As the awareness of perchlorate contamination grows, it is important to be prepared and take a proactive approach to find a solution. Many of the "at risk" sites currently impacted by perchlorate are impacted by other pollutants that have previously been identified. However, low concentrations of perchlorate have migrated farther than most of the other identified pollutants, because of highly mobile characteristics of this compound (e.g., size).

Ammonium perchlorate has been found in drinking water wells in areas where aerospace material and munitions development, testing, and manufacture occurred, and for where companies or users carelessly discharged the unregulated chemical onto the ground, which allowed the chemical to seep into the ground water. There it dissociated into ammonia and perchlorate. A second area of perchlorate contamination assessment is focused on states with mining activities where explosives are used extensively.

This manuscript summarizes literature on perchlorate occurrence, sources of perchlorate, results of 386 samples analyzed from 16 states, and finally describes treatment technologies available for its control.

REVIEW OF REGULATORY IMPETUS AND OCCURRENCE

There is no formal federal standard for perchlorate in drinking water. The California Department of Health Services (CDHS) has adopted a provisional action level of 18 μg/L for perchlorate in drinking water. This guideline is based on highly uncertain preliminary health effects data available. To obtain reliable risk data, USEPA is reassessing the toxicity of perchlorate, and has compressed the typical five- to seven-year timetable for assessments to just under a year (Renner, 1998). The final assessment is due in September, 1998.

A database search by the Chemical Propulsion Information Agency, combined with information provided by the USEPA Superfund database, personal contacts and maps from several sources, produced a list of several sites where perchlorate is manufactured, used in propulsion applications and other sources of perchlorate contamination such as industrial sites and superfund sites. A second area of perchlorate contamination assessment is focused on states with mining activities where explosives are used extensively. A list of targeted states will tentatively include Arizona, California, Nevada, Colorado, Utah, and Wyoming. The important places in the U.S. where the manufacture and use of perchlorate chemical is associated is indicated in Figure 1.

California. Ammonium perchlorate has been found in California drinking water wells in areas where aerospace material and munitions development, testing, and manufacture has occurred. Low to high levels of perchlorate were discovered in groundwater in several areas where it was used in conjunction with solid rockets, including Pasadena, Santa Susana, Hollister, San Barnardino County, Riverside City, Sacramento County, San Gabriel Valley, Los Angeles County and in the vicinity of San Jose. Tests are planned on groundwater near Vandenberg Air Force Base in Santa Barbara County, a major military rocket launching facility, and Edwards Air Force Base in Kern County, a test installation.

The concentrations are sufficiently high--above 18 μg/L, although substantially below levels known to produce serious health problems--to cause the closing of 18 municipal wells in the counties (HLA, 1997; The Press-Enterprise, 1997; Sacramento Bee, 1997). Perchlorates are present in some groundwater sources at levels as high as 8000 to 10,000 μg/L. However, it had not been a matter of concern until perchlorate compounds appeared this year in drinking water wells at up to 280 μg/L. In all, California health officials have tested 232 wells statewide. They have detected perchlorate in 69 of them, with 24 registering concentrations above the 18 μg/L limit (CDHS, 1997H). Subsequent testing in the San Gabriel Valley revealed six wells which contain perchlorate in excess of the state's provisional action level of 18 μg/L.

The sources which have cause groundwater contamination and are suspected of using perchlorate have been identified in Table 1. The sources are briefly described below:

Los Angeles Area: The *Jet Propulsion Laboratory* (JPL) is a 176-acre site in Pasadena, California. JPL's primary activities include the exploration of the earth and solar system by automated spacecraft and the design and operation of the Global Deep Space Tracking Network. Hazardous

Legend:

- ✹ Mining Activities (Explosives)
- ◆ Former/Current Storage Facilities
- ◈ Perchlorate Manufacturers
- ℞ Government Research Laboratories
- ⊠ Propulsion Manufacturers

- ⚲ Selected Superfund Sites
- ☐ AWWSCo Samples Tested Positive
- ○ Nevada Samples Tested Positive
- △ Utah Samples Tested Positive
- χ California Sites Tested Positive

Sources: CDHS, The Press-Enterprise, USEPA, Chemical Propulsion Information Agency, Maps, Personal Contacts

Figure 1. U. S. Perchlorate Manufacturers, Users Facilities and Mining Activities
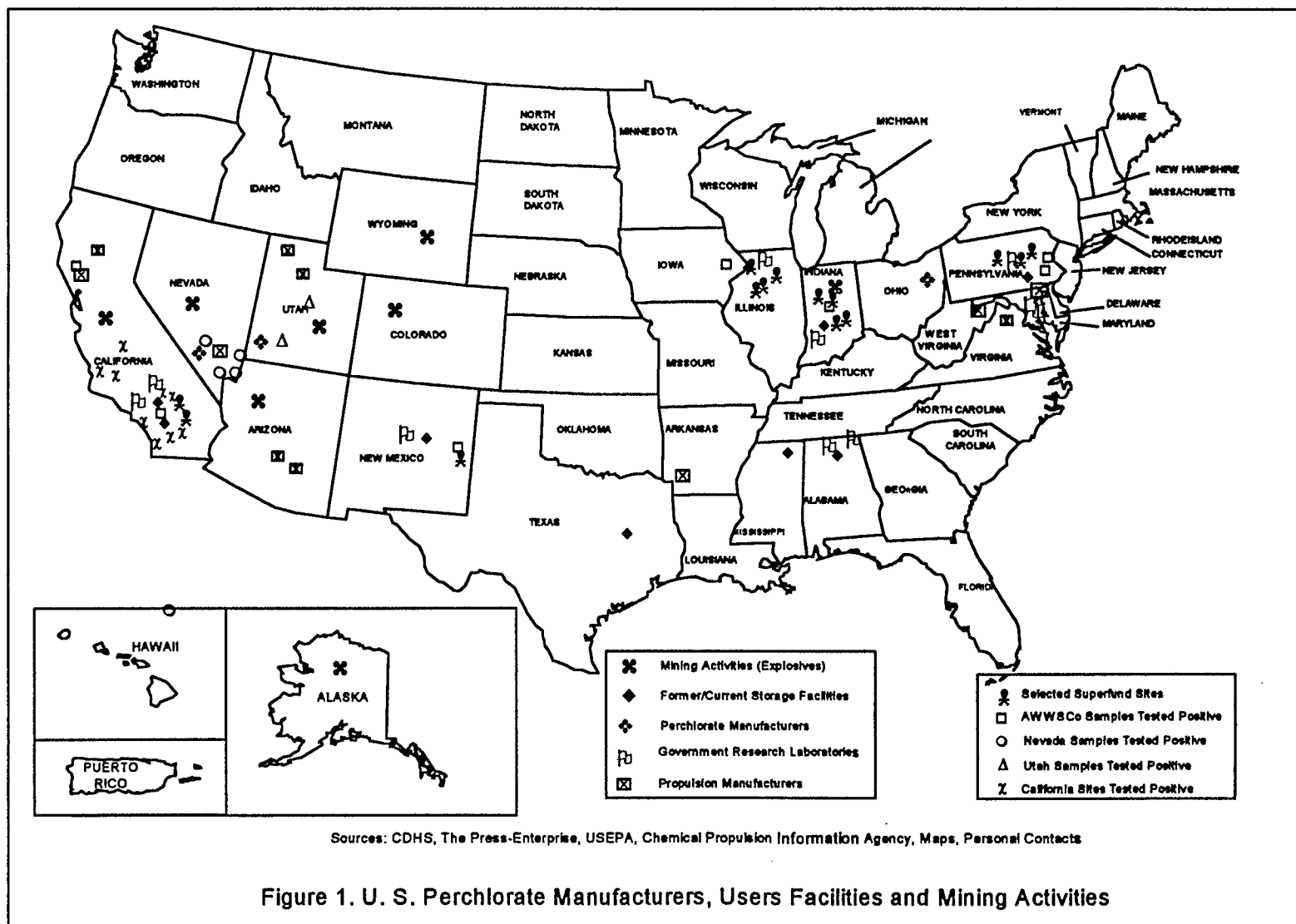
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Table 1. Occurrence and Potential Sources of Perchlorate in Drinking Water Sources
[Sources: CDHS, 1997; HLA, 1997; The Press-Enterprise, 1997; Sacramento Bee, 1997]

TYPE	LOCATION	SUSPECTED SOURCES	RANGE (μg/L)
Groundwater	San Bernardino County [Loma Linda, Redlands East Valley District]	Lockheed Propulsion Co. (Menton)~* WW-II Camp Ono Army Base Spills^ George Air Force Base*~ Norton Air Force Base*~ Barstow Marine Corps Base~*	5-216
Groundwater	Riverside City, CA	Lockheed Propulsion Company~* March Air Force Base* Stringfellow Superfund Site* Norton Air Force Base*	4-21
Groundwater	Los Angeles County [Irwindale, La Canada Flintridge, La Puente, Newhall, Pasadena, Santa Clarita, West Covina]	Whittaker Bermite Site (Santa Clarita)~* AZUSA Landfill* Jet Propulsion Lab (Pasadena)~* Burbank Superfund Site~* San Gabriel Valley*~	4-159
Colorado River	Hoover Dam, LV Grand Wash, LV Lake Havasu, CA	Kerr McGee Facility - Henderson, NV*~ (Perchlorate Manufacture) Pacific Engineering (Perchlorate Manufacture) - Henderson, NV*	5-9
Groundwater	Sacramento Rancho Cordova	Aerojet General Corporation~* Mather Air Force Base (1 mi S)^ Sacramento Army Depot (2 mi W)^ McClellan Air Force Base (<2 mi NW)^ McDonnell-Douglas Former Facility* Purity Oil Co. Former Facility* McClellan AFB (20 mi N)~^	4-280
Wells/Surface	Las Vegas, NV	Kerr McGee Facility - Henderson~* Pacific Engineering - Henderson, NV*	0-13
Groundwater	West Valley City, UT	Alliant Techsystems*	4-200
Lake	Lake Mead, NV	Kerr McGee Facility - Henderson~* Pacific Engineering - Henderson, NV*	0-165
Surface Upper Portion Lower Portion	Las Vegas Wash, NV North Shore Bridge, NV	Kerr McGee Facility - Henderson~* Pacific Engineering - Henderson, NV*	11-47 1000-1700
Groundwater	San Gabriel Basin, CA	Burbank Superfund Site~* AZUSA Landfill* Jet Propulsion Lab (Pasadena)~*	<4-1000
Groundwater	San Benito County, CA	Whittaker Ordnance Facility-Hollister*~	8-88

* CDHS, 1997; HLA, 1997; The Press-Enterprise, 1997; Sacramento Bee, 1997; USEPA Superfund Database

^ sources confirmed by maps and personal contacts

~ predicted by information from Chemical Propulsion Information Agency/USEPA Superfund Database

substances located at JPL include waste solvents, solid rocket fuel propellants, cooling tower chemicals, sulfuric acid, Freon, mercury, and chemical laboratory wastes. In 1990, JPL detected significantly elevated levels of contaminants in the groundwater underneath and down-gradient of the site. The groundwater contamination from the JPL has traveled off site and has affected several drinking water wells. The *San Gabriel Valley* site is an area of contaminated groundwater that runs along San Jose Creek in La Puente. This site is one of four Superfund sites located in the 170-square-mile San Gabriel Valley. Over 30 square miles of groundwater under the Valley may be contaminated. The sites include four large areas of groundwater contamination that underlie significant portions of the Cities of Alhambra, Arcadia, Azusa, Baldwin Park, Industry, El Monte, La Puente, Monrovia, Rosemead, South El Monte, West Covina, and other areas of the San Gabriel Valley. Contamination of the groundwater by volatile organic compounds (VOCs) was first detected in 1979 when Aerojet Electrosystems in Azusa sampled nearby wells in the Valley County Water District (USEPA, 1998).

Riverside City: The 7,000-acre March Air Force Base has been used for aircraft maintenance and repair, refueling operations, and training activities since 1918. The Air Force conducted a preliminary investigation of 39 potentially contaminated areas on base which included three fire training areas, seven inactive landfills, underground solvent storage tanks, an engine test cell, and spills. Significant contamination was found at seven of the 39 areas. Three regions of groundwater contamination beneath the base were identified and a well on the base was shut down in 1984. Groundwater contamination has migrated to wells located off base. From 1956 until 1972, the 17-acre *Stringfellow site* was operated as a hazardous waste disposal facility. Over 34 million gallons of industrial waste were deposited in evaporation ponds. Spray evaporation procedures were used to accelerate the reduction of pond content volume (USEPA, 1998).

Sacramento Area: The *Aerojet General Corp.* site covers 8,500 acres near Rancho Cordova, 15 miles east of Sacramento. Since 1953, Aerojet and its subsidiaries have manufactured liquid and solid propellant rocket engines for military and commercial applications and have formulated a number of chemicals, including rocket propellant agents, agricultural, pharmaceutical, and other industrial chemicals. In addition, the Cordova Chemical Company operated a chemical manufacturing facility on the Aerojet complex from 1974 to 1979. Both companies disposed of unknown quantities of hazardous waste chemicals, including trichloroethylene (TCE) and other chemicals associated with rocket propellants, as well as various chemical processing wastes. Some wastes were disposed of on the site in surface impoundments, landfills, deep injection wells, leachate fields, and directly on the ground. Other wastes were burned. Perchlorate a waste product of solid rocket fuel was found in drinking water wells off-site above the provisional reference dose in January 97. Public and private drinking water supply wells have been contaminated. Groundwater and surface water contain volatile organic compounds (VOCs) and other rocket propulsion waste products such as perchlorate and N-Nitrosodimethylamine. The *Mather Air Force Base* (MAFB) was first activated in 1918 as a combat pilot training school and was officially closed on September 30, 1993. Past operation and maintenance of aircraft at MAFB required the use of toxic and hazardous materials, such as petroleum, oils, lubricants, solvents and protective coatings. Soil and groundwater contain various volatile organic compounds (VOCs), gasoline, diesel fuel, metals, pesticides, and other contaminants.

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The 485-acre *Sacramento Army Depot* site, established in 1945, is a supply depot primarily responsible for the receipt, storage, issuance, maintenance, and disposal of military supplies. These practices have resulted in the contamination of some on-site soils at the Former Oxidation Lagoons and Burn Pits and other areas, as well as the groundwater beneath the site. The groundwater contamination at the site is in the shallow and intermediate water-bearing zones, and has migrated off site. The 2,952-acre *McClellan Air Force Base* (MAFB) site was established in 1936 and operates today as an Air Force Logistics Command Base with a primary mission of management, maintenance, and repair of aircraft, electronics, and communication equipment is also located nearby. The operation and maintenance of aircraft have involved the use, storage, and disposal of hazardous materials including industrial solvents, caustic cleansers, low-level radioactive wastes, and a variety of fuel oils and lubricants (USEPA, 1998).

San Barnardino area: The *Barstow Marine Corps Logistics Base* site covers 5,687 acres east of Barstow, California. The majority of wastes historically generated by the base have been vehicle-related and war surplus. Some hazardous or suspected hazardous wastes were contained in war surplus materials received at the base including ammunition, various sources of low-level radiation (luminescent dials, watches, and scopes) and chemicals such as pesticides, herbicides and raw materials. Groundwater contains volatile organic compounds (VOCs) such as trichloroethylene (TCE) and perchloroethylene (PCE). *George Air Force Base* occupies 5,347 acres. The base, which was closed in December 1992, supported tactical fighter operations and provided training for air crew and maintenance personnel. Sixty-three potential areas of contamination have been identified at this facility. The *Newmark Groundwater Contamination site* consists of two areas of groundwater contamination and a World War II Army base, which has been developed for light industry and residential uses. The two groundwater plumes border Shandin Hills. On the east side of the site, a contaminated groundwater plume extends for 5 miles and is referred to as the Newmark Plume area. On the west side of Shandin Hills is a 4-mile long contaminated groundwater plume known as the Muscoy Plume area. The discovery of contaminants, including chlorinated solvents, tetrachloroethylene (PCE), and trichloroethylene (TCE), resulted in the closing of 20 water supply wells within a 6-mile radius of the site. The City of Riverside, with a population of approximately 250,000, relies on wells down gradient from the Newmark plume for approximately 75 percent of its total water supply. The 2,165-acre *Norton Air Force Base site* had the responsibility of providing maintenance and logistics for liquid-fuel intercontinental ballistic missiles. Past hazardous waste management practices may have contributed to existing contamination problems throughout the base. Groundwater contains various volatile organic compounds (VOCs), such as trichloroethylene (TCE). Soil also is contaminated with VOCs, PCBs, and heavy metals including chromium, arsenic and copper. Several City of Riverside drinking wells have shown levels of TCE slightly above the MCL (5 ppb)(USEPA, 1998).

Nevada and Utah. The presence of perchlorate in Nevada's water sources appear to be related to contamination arising from the manufacture of the ammonium perchlorate. Kerr-McGee Corporation and the Pacific Engineering & Production Co. of Nevada, or PEPCON, owned by American Pacific Corp., produced the oxidizing compound until 1988 when the plant was leveled by a series of explosions. Nevada environmental officials have identified both the Kerr-McGee and

PEPCON sites as sources of the contamination. Water tested recently from a well at the Kerr-McGee chemical plant near Henderson, NV revealed a high concentration of perchlorate, a compound the company has stored on site for decades as part of its ongoing production of ammonium perchlorate, a rocket-fuel oxidizer. American Pacific Corp. moved its ammonium perchlorate manufacturing operations 14 miles northwest of Cedar City, Utah, after the 1988 blasts (Review-Journal, 1997).

Water samples tested from the Las Vegas Wash - downstream from the Kerr-McGee facility - had perchlorate levels of 1,680 $\mu g/L$ (Review-Journal, 1997). That water is not part of the local drinking supply - it is flowing back into Lake Mead - but an earlier investigation into water delivered for public use found levels as high as 11 $\mu g/L$. At this point, there is no evidence the valley's drinking water presents a hazard.

About 85 percent of Southern Nevada's drinking water comes from Lake Mead. The remaining 15 percent comes from deep wells. But the discovery of perchlorate in Lake Mead, in the Las Vegas Wash, and in some well water has prompted local and state officials to vigorously pursue the matter before the situation worsens. The discovery of high concentrations of perchlorate in the Kerr-McGee well confirms suspicions that industrial plants in the area are the likely sources of the chemical. Kerr-McGee and Pacific Engineering, which relocated from Henderson to Utah a decade ago, were for years the country's only producers of ammonium perchlorate (Review-Journal, 1997). The plant has existed for 50 years, and operated for half that time with no regulation of its disposal practices. The authority was alerted to the presence of perchlorate after the Los Angeles Metropolitan Water District detected it at Hoover Dam and downstream in the Colorado River system.

MAGNA, Utah - Discovery of the rocket fuel ingredient perchlorate in wells on Alliant Techsystems and Kennecott Utah Copper properties prompted Kennecott officials to inform 1,000 workers not to drink tap water. Kennecott Copper Corp., which owns the site (excluding portions of Magna), has operated a wide variety of mineral processing and production facilities in the area since around 1900. The principal aquifer, which supplies water to the Magna municipal water system, underlies many of the sources at the site. In addition, surface water analysis near wetlands shows releases of copper to the ditch near the large tailings pond. Current Kennecott activity in the North Zone site involves smelting and refining the concentrated copper ore that has been mined from the open pit approximately 20 miles south of the site. Alliant, which builds rocket motors in West Valley City, found elevated levels of the chemical in 400-foot-deep wells on its property. Alliant, formerly known as Hercules, has used ammonium perchlorate in its rocket-motor production since the 1960s. Until 1988, the company discharged the chemical onto the ground of its site, which allowed the chemical to seep into ground water. The tests performed last month found the chemical's levels to range from 4 to 200 $\mu g/L$ beneath Alliant property. It also found lower levels of perchlorate in adjacent wells that serve Kennecott's northern facilities, including the smelter, the power plant and the tailings pond. In response, Kennecott informed their employees to drink only bottled water. In Kennecott's wells, perchlorate levels averaged 13 $\mu g/L$, which is below California's health standard. Because of uncertainties about the extent of the contamination, Kennecott decided to take precautionary measures to protect its employees.

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The Tooele Army Depot (TEAD) is in Tooele, Tooele County, Utah, 35 miles southwest of Salt Lake City. Since 1943, TEAD has had a fourfold mission: store ammunition, demilitarize ammunition, rebuild military equipment, and store military equipment. In fulfilling its mission, TEAD decommissions munitions by cutting the casings and removing and recycling the explosive material. The casings are then rinsed with water to remove residual explosives. Between 1948 and 1965, rinse waters were discharged into the "TNT Washout Area," which covers less than 1 acre in the North Area. The Army has detected trinitrotoluene (TNT) and cyclomethylenetriamine (RDX), an experimental explosive, in soil near the TNT Washout Area, threatening ground water. A ground water assessment required by the decree shows that a plume of ground water contaminated with trichloroethylene (TCE) and trichloroethane (TCA) has migrated down gradient approximately 2 miles. The leading edge of the plume lies several hundred yards beyond the TEAD boundary and may be migrating several hundred feet per year (USEPA, 1998).

Perchlorate was found entering Lake Mead at relatively high levels -- 1,000 $\mu g/L$ -- in Las Vegas Wash at North Shore Bridge, a mile upstream of where the wash empties into the lake, which is part of the Lower Colorado River system. Perchlorate levels as high as 3.7 $\mu g/L$ and 630 mg/L have been detected respectively in monitoring wells for Kerr-McGee Chemical Corporation near Henderson and the site of the old Pacific Engineering plant in Henderson, where the chemical has been historically produced (Review-Journal, 1997). Both sites are upstream of Las Vegas Wash. California's, Metropolitan Water District officials detected amounts ranging from 6 to 10 $\mu g/L$ in Colorado River water, one of two sources serving the huge Los Angeles-area water supplier. The chemical was traced upriver to Lake Mead, where higher levels were found, and then up the Las Vegas Wash, a major storm drainage canal for the Henderson-Las Vegas area that flows into Lake Mead.

CHEMICAL CHARACTERISTICS

Perchlorate (ClO_4^-) is used in the manufacture of explosives in various forms: hydrazine perchlorates; ammonium perchlorate; 2-(5-cyanotetrazolato) penta amminecobalt (III) perchlorate (CP); cis-bis (5-nitrotetrazolato) penta amminecobalt (III)perchlorate (or BNCP); hydroxyl ammonium perchlorate (HAP); potassium perchlorate; nitronium perchlorate and guanidine (guanidinium) perchlorate. Perchlorate is a strong oxidant and is primarily used in explosive, pyrotechnic mixtures and as an ingredient in jet and rocket fuel and automotive safety air bags. It is highly water soluble (~ 1 g/L). The high solubility of perchlorate is not affected by pH or temperature. Perchlorate ion in dilute solutions is very stable and inert, and does not serve as an oxidizing agent. Perchlorate is generated electrochemically by the anode reaction between chlorate and water $[ClO_3^- + H_2O \rightarrow ClO_4^- + 2H^+ + 2e^-; E_o = -1.23\ V]$ and can also be manufactured by reacting ammonia with perchloric acid $[NH_3 + HClO_4 \rightarrow NH_4ClO_4]$ or by the reaction of sodium perchlorate with ammonium chloride $[NaClO_4 + NH_4Cl \rightarrow NH_4ClO_4 + NaCl]$. There is also likelihood of forming perchlorate during the manufacture of chlorine dioxide or its storage.

Methylene blue forms a violet precipitate with perchlorate ion. Perchlorate creates a serious

fire hazard by reaction with organic materials such as: fuels, reducing agents, etc. When heated it emits highly toxic fumes of chlorides.

Chlorate (ClO_3^-), and chlorite (ClO_2^-) are sister species of perchlorate. These are byproducts of chlorine dioxide and hypochlorous acid. Excessive ratios of Cl_2: ClO_2^- may also favor ClO_3^- and ClO_4^- formation in the generator. The production of ClO_4^- is also expected to be proportional to the presence of high concentrations of free chlorine at low pH in aqueous solutions, and ClO_4^- can also be generated in dilute chlorite/chlorate solutions held at low pH [$ClO_3^- + HOCl \rightarrow ClO_4^- + Cl^- + H^+$]. Perchlorate can also be formed by ozone oxidation of hypochlorite ion (Siddiqui, 1996)[$ClO_3^- + O_3 \rightarrow ClO_4^- + O_2$]. It is thermodynamically feasible to form perchlorate from these reactions [$H_f^o < 0$ (-31 kcal/mol)]. Sufficient chemical kinetics data for perchlorate formation is not available from these reactions since no attempt has been made to measure or quantify its presence.

HEALTH AND TOXICITY ISSUES

Little research has been conducted on the effect of perchlorate ion on long-term, low-level exposure, whether on animals or humans. Those studies that exist focused on perchlorate as a medicine -- involving much higher doses than that found in groundwater -- and determined its effect only on the thyroid, not the liver, brain, heart and other sensitive organs.

The Air Force in September, 1997 initiated several toxicology studies on animals through which they hope to learn more about perchlorate's effect on people. The research should yield clues on how the chemical affects young children and pregnant women, and major organs. Findings are due in July 1998.

No quantitative risk estimate for carcinogenicity was derived for perchlorate compounds because of the limitations of the data. However, because thyroid tumors were observed in both mice and rats following long-term administration of sodium or potassium salts, a weight-of-evidence classification of B2, probable human carcinogen, according to USEPA is appropriate (USEPA, 1992). All of the data pertinent to the possible carcinogenicity of the perchlorates is related to the effects of the perchlorate ion on the follicular cells of the thyroid gland (Stanbury and Wyngaarden, 1952; Saito et al., 1983). Toxicology Excellence for Risk Assessment (TERA) peer review panel concluded that the database for perchlorate was insufficient to support the development of an perchlohate oral reference dose (RFD) (TERA, 1997). According to them several major questions were left unanswered by the existing data including the shape of the dose-response curve in humans, the effects of perchlorate after long-term exposure, and the possibility of effects in organs or systems other than the thyroid. Perchlorate can block the passage of iodine to the thyroid, inhibiting its proper functioning. The toxicology database for perchlorate has been characterized by the EPA National Center for Environmental Assessment as severely limited by the fact that there is no chronic study which has been conducted at doses low enough to demonstrate a No Observed Adverse Effect Level which examines the full range of potential toxicities.

Perchlorate has been used in medical treatments of human thyroid gland disorders. Elevated levels of perchlorate have been found to prevent the gland's production of "growth" hormones. Perchlorate, in very high doses, has been used as a medicine to treat Graves' disease, a condition in which excessive amounts of thyroid hormones are produced. Perchlorate inhibits the excessive synthesis and secretion of thyroid hormones by competitively inhibiting the accumulation of iodide in the thyroid (Stanbury and Wyngaarden, 1952). The use of repeatedly administered potassium perchlorate to inhibit thyroid activity has been associated with infrequently occurring side effects, including skin rashes, sore throat, gastrointestinal irritation and hematological effects (Morgans and Trotter, 1960; Crooks and Wayne, 1960).

Fatal acute liver atrophy occurred in a patient who received 600 mg/day sodium perchlorate for 13 months (Kotzaurek, 1965). Perchlorate passes through the human body quickly via the urinary tract in the form of perchlorate and chloride ion. Between 1961 and 1966, several cases of fatal aplastic anemia were reported in female patients receiving long-term potassium perchlorate treatment for hyperthyroidism (Hobson, 1961). Barzilai and Sheinfeld (1966) also reported a fatal case of agranulocystosis in a woman treated with 1000 mg/day potassium perchlorate for a few months. In the worst cases, it can cause brain damage in fetuses and a potentially fatal form of anemia in adults. However, "there is a data gap between known effects of very high levels and possible effects at the levels being detected. This chemical also shown to produce possible chronic bone marrow effects.

ANALYTICAL PROCEDURES

There are several methods available to analytically measure perchlorate from drinking water sources. The most sensitive and reliable method is based on ion chromatography system with appropriate separating columns. Other methods use precipitation titration, selective electrodes, and kinetics. These methods are subject to various interferences and the quantification limits are not suitable for drinking water purposes.

Since perchlorate is not a regulated contaminant, no formal USEPA laboratory procedure exists. The measurement of perchlorate method employed in this study involved the use of standard bore ion chromatography system (Dionex-500 IC), fitted with an AS-5 anion separating column, suppressed by an anion self-regenerating suppressor (ASRS-I), and measured by conductivity DS3 (detection stabilizer unit). Approximately 750 uL was injected. The eluent consisted of 120 mM sodium hydroxide, 2 mM p-cyanophenol (1.0 ml/min) with 0.035 N sulfuric acid as a continuous column regenerating agent (10 ml/min). The least quantification limit was 4.0 μg/L. The 120 mM NaOH was prepared fresh to avoid CO_2 contamination. This method is similar to the procedure adopted by California Department of Health (CDHS, 1997).

Perchlorate binds strongly to many ion exchange resins commonly employed in separating columns. This may lead to slow elution or suppressed detection. It is imperative that a mass balance be performed to estimate the percentage adsorption onto the separating columns and to use the most optimum column. Perchlorate is present as an impurity in chlorate and other reagents and care should

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be taken to correct for its background since they may elute close to each other. If the samples contain high concentration of sulfate and chloride, the samples should be treated with calcium chloride to remove sulfate ions by precipitating calcium sulfate and with silver containing cartridges to remove chloride ions by precipitating silver chloride to minimize peak masking interferences in the measurement of perchlorate.

RESULTS AND DISCUSSION

Occurrence. The data collected and analyzed indicate that occurrence of perchlorate is a localized problem. But if the contamination is left unchecked, the occurrence of perchlorate will become widespread in view of the high mobility and transport of this compound in aqueous phase. Of the total 386 samples collected and analyzed from American Water System's ground water sources from sixteen states and a diverse set of locations, only ten tested positive for perchlorate (<3%). Sampling and testing was done in January, February, and March of 1998. The results of all sites tested positive are summarized in Table 2. The perchlorate concentrations ranged from 2 to 6 μg/L, well within the guideline value of 18 μg/L, suggested by California Department of Health. It is possible that the concentrations may vary due to seasonal variations or over time as the plume moves closer to drinking water sources.

Sources. Important sources within the radius of 30 mi were investigated. Preliminary calculations have indicated that for perchlorate levels to be ~ 5-10 μg/L, the concentrations of perchlorate required upstream are much smaller than 500-1,000 μg/L seen at several places in Californian groundwaters. Considering the large-scale contamination of ground water these sources have caused it is reasonable to assume that contamination can occur easily from a source 30 mi away from the actual site. For example, in the San Gabriel Valley, the soil is very sandy and permeable. The perchlorate, which does not bind to the soil appreciably and thus moves quickly with groundwater flows, apparently has migrated 15 miles away to the La Puente Valley Water District. The source of contamination from hazardous waste landfills can be more severe if perchlorate waste is buried and other chemicals are present that can react to form additional perchlorate. Hazardous waste landfills can be considered as big chemical reactors where conditions are present for forming several chemical compounds. For e.g., if ammonia is present, it can easily react with perchloric acid or chlorate to produce ammonium chlorate $[NH_3 + ClO_3^- \rightarrow NH_4ClO_3; NH_3 + HClO_4 \rightarrow NH_4ClO_4]$ $[2HClO + ClO^- + H_2O \rightarrow ClO_3^- + H_2O + 2Cl^-; ClO_3^- + HOCl \rightarrow ClO_4^- + Cl^- + H^+]$. Chlorate can also be converted to perchlorate by electrochemical conditions exist in landfills according to the reaction: $[ClO_3^- + H_2O \rightarrow ClO_4^- + 2H^+ + 2e]$. Sodium *chlorate* is found in a variety of commercial herbicides. Some trade names for products containing sodium chlorate include Atlacide, Defol, De-Fol-Ate, Drop-Leaf, Fall, Harvest-Aid, Kusatol, Leafex, and Tumbleaf. The compound is also present in combination with other herbicides such as atrazine, 2,4-D, bromacil, diuron, and sodium metaborate. Sodium chlorate is a strong oxidizer also used in the manufacture of explosives.

Several of the California-American Water Company's *San Marino* District (proximity of Pasadena, CA) wells contained detectable amounts of perchlorate (>4 μg/L)(Table 2). The San Marino district of California-American Water Co., Los Angeles supplies water to the communities

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Table 2. Occurrence and Suspected Sources of Perchlorate in American Groundwater Systems

WELL LOCATION	STATE	POSSIBLE SOURCES[&&]	1ST SAMPLING [$\mu g/L$]	2ND SAMPLING[$]$ [$\mu g/L$]

San Marino
  Oak Knoll Circle
  Patton Well
	CA	San Gabriel Superfund site*~
		AZUSA Landfill (10 mi E)*
		Jet Propulsion Laboratory (2 mi N)*~
			
			4.8
			6.2
				
				–
				–

Clovis
  Well 44
  Well 45
  Well 48
	NM	Cannon Air Force Base (10 mi E)*
		Fort Summer Remains (30 mi E)*~
		Explosive Mining Activity (Vicinity)*~
		Research Laboratories (30-60 mi E)*
		AT&SF Site (Proximity)^
			
			3.4
			2.4
			3.7
				
				1.9
				2.1
				ND

Yardley Well 9	PA	Naval Air Develop. (10 mi W)*^ North Penn-Area 2 (20 mi E)^ Moyers Landfill (20 mi E)^ Warminster Site (10 mi E)^	 5.0	 ND
Monterey LaSalle Well	CA	Abandoned Fort Ord (<1 mi)* Naval Training center (10 mi E)* Ex-Ammunition Facilities (<30 mi)*~	 2.7	 –
Greenwood Marlin Well #1	IN	Naval Weapons Research (10 mi N)* Military Camp (19 mi S)* Fort Benjamin (20 mi N)* Explosive Mining (proximity)*~ Superfund Site, Indianapolis (<10 mi N)^ Electroplating Superfund Site (20 mi S)^	 4.0	 ND

Davenport/Clinton
  Well 3
  Well 9
	IA	Savanna Army Depot. (20 mi N)*^	
			5.8'
			6.4'
				
				ND
				ND

* Sources confirmed by maps and personal contacts

~ Predicted by information from Chemical Propulsion Information Agency/USEPA Superfund Database

^ USEPA Superfund database

&& Although the sources are in the proximity of contaminated source waters, no actual testing has been done to confirm the movement of perchlorate to the water sources. Some groundwater contours do pass through these supposedly contaminated sites

$ Many of the positive sites were resampled approximately 2 months after the first sample was collected. ND indicates that perchlorate was not detected. – indicates that a resample was not performed.

' The initial samples from Davenport/Clinton contained a large masking peak which caused difficulties in assessing an accurate perchlorate level.

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of San Amrino, Rosemead and portions of Temple City, San Gabriel, El Monte and Pasadena. The service area of the district lies in the west San Gabriel valley approximately 10 miles north east of LA. The water served by the district is about 90% local well water and 10% imported supply from the MWD. The wells are located in Oak Knoll, Oswego, Patton, Lamanda Park, Lombardy, Winston, Del Mar, Longden, Roanoke, Rosemead, Grand, Richardson, mariposa, Guess, Mission View, Ivar, Howland. Ground water in the nearby Pasadena area contains much higher levels of perchlorate and one well was closed down last year because perchlorate was in excess of California's advisory limit. The source of their contamination is supposedly Jet Propulsion research facility, where monitoring wells show very high levels (>1000 μg/L), San Gabriel Superfund site. Aerojet incinerated several tons of perchlorate waste in open-air pits in accordance with federal rules at the time and this may have caused widespread deposition at other places by atmospheric transport (Armstrong, 1997). But the burning was not complete and perchlorate apparently seeped into the ground through contaminated soil. At this time no studies have been performed to trace the source of contamination in the San Marino wells, and potential sources are listed simply to assist in future studies.

The *Monterey* District of California-American Water Company (i.e., LaSalle well) is more than 300 miles away from Los Angeles. The water supply in Monterey consists of 36 wells, 2 reservoirs. The available water supply is produced from the following: 71% is supplied from wells from the Carmel Valley and Seaside Aquifers, and 29% is supplied from San Clemente and Los Padres Dams. The distribution system contains in excess of 507 miles of main, ranging in size from 1 inch to 32 inches in diameter and passes in the vicinity of several contaminated sites. The LaSalle well is in the city of Seaside, not too far from where Fort Ord was located. Transport and atmospheric deposition from explosive mining activities and eventual leaching into the surface and groundwater sources is a possibility. There are several superfund sites located in the 30 mi vicinity of the Monterey district. Future studies should examine these suspected sources: Fort Ord Site, landfills, or industrial contaminated sites.

The 29,440-acre *Fort Ord site* was established in 1917 by the US Army as a maneuver area and field artillery target range. Prior to closing in September 1994, the base's primary mission was training infantry military personnel. Several areas of contamination exist on site. The facility contained chemical storage areas, target ranges, and landfills. An 8,000-acre firing range, and other limited areas on-site, pose threats from unexploded ordnance. On-site groundwater is contaminated with volatile organic compounds (VOCs). The 125-acre *Crazy Horse Landfill* site has operated as a sanitary landfill since 1950. In 1977, the landfill received a permit from the State allowing it to accept various wastes. Some pesticide containers have been disposed of at the facility. Reportedly, from the early 1970s to 1982, large quantities of waste were disposed of on the site from its vulcanizing process, which included rubber, carbon black and other fillers, oils, and mixed solvents. *The Salinas Plant site* consists of a 43-acre former tire manufacturing plant on a 256-acre parcel of land. Solid and hazardous wastes from the manufacturing processes were disposed of in off-site facilities. An estimated 400 drinking water wells have been identified in the area.

Several sites were located in the vicinity of Indiana-American Water Company's Marlin well field, Greenwood, IN that could contribute to perchlorate contamination. There are several superfund

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sites and hazardous waste landfills are located in the vicinity of wells. The landfills accept municipal and industrial wastes including solvents, acids, bases, paints, and heavy metals. Almost all hazardous waste landfills contain battery waste and magnesium perchlorate is one of the ingredients used in manganese dioxide-magnesium perchlorate primary batteries (Crompton, 1996). Ammonia, which is a common contaminant found in landfills can potentially react with chlorate present in several insecticides and pesticides to form perchlorate. Waste sludges such as clarifier sludges can also contain perchlorate from a variety of waste material.

The source of supply for the Clinton District, Iowa, is seven deep wells and the raw water is discharged to reservoirs from where distributive pumps deliver water to the main service distribution system. There is room for contamination from storm water runoff. The groundwater wells at *Iowa-American, Clinton and Davenport* are located within 20-30 mi of the 13,062-acre Savanna Army Depot site which is an Army munitions installation located on the eastern bank of the Mississippi River. The facility has handled, processed, and stored munitions, explosives, and industrial chemicals since operations began in 1918. Renovation and loading of artillery shells and bombs began at the site in the 1930s and has occurred intermittently. Several areas of the facility have been used for the demolition and burning of obsolete armaments. Approximately 70 areas within the facility have been identified as potential sources of hazardous waste. Public access to the site is restricted. There are approximately 650 people within 3 miles of the site, and a large wintering population of bald eagles resides on the facility. Groundwater is contaminated with various explosives, trichloroethylene (TCE), chloroform, and nickel. Sediments and surface water are contaminated with various explosives. Soil is contaminated with explosives and polycyclic aromatic hydrocarbons (PAHs). Potential health threats include drinking contaminated groundwater and coming in direct contact with surface water, soil, and sediments. Rock Island Arsenal, the US Army's largest armaments manufacturing facility and the command post of the US arsenal system is also located in the vicinity of Davenport. Further studies of perchlorate transport in this area are needed.

Groundwater at New Mexico-American Clovis site contained perchlorate in the amount of 2 to 4 μg/L (Table 2). NM-AWC provides water from 39 wells ranging in depth from 315 ft to 438 ft. Several wells show amounts of mercury in excess of 0.002 mg/L, trace amounts of barium and arsenic. In an effort to provide proper maintenance of station facilities, an herbicide known as "Staykill" was applied to well sites and booster stations to control weed growth. This chemical has a long-lasting residual, and contains chlorate as an ingredient. Several cases of ground water contamination have been discovered within the vicinity of several NMAWC wells. The most notable of these is the Santa Fe Lake. The Lake has been contaminated by the railroad with heavy metals from the flushing of ore cars. Perchlorate compounds employed during explosive activities are normally part of mined ores and trace amounts of perchlorate can leach into source waters. Investigation of other sources in proximity of these wells indicated the presence of Cannon Air Force Base (10 mi E), Fort Summer remains (30 mi E), explosive mining activity in the vicinity, and research laboratories (30-60 mi E) which can potentially contribute to contamination (Table 2). A landfill is also located about four miles to the North. An industrial superfund site, about 1 mi S of the AT&SF switching board yard, Clovis, conducted railroad refueling and hopper car washing at railroad since 1950's. This site has been found to be contaminated with several hydrocarbons, trace heavy metals, and other

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pollutants. Perchlorate may have been generated from hopper and washing operations from trucks hauling perchlorate materials. Perchlorate is also an ingredient in the manufacture of paint.

Ground water supply in the Yardley, PA area is supplied by 6 wells located in 3 different well fields. All wells are drilled into the Stockton formation and are between 300-600 ft deep. The well sources currently have no wellhead programs in place. A wellhead protection program is designed to protect ground water supplies from contamination. The program should be a proactive effort to apply proper management techniques and preventive measures in order to protect ground water supplies. The wells located in the College Avenue Station area are contaminated with VOCs and air striping is employed to reduce their concentrations. Pressures in the gradient range from < 20 psi when the water level in the Oxford Valley Standpipe drops below 30 ft to close to 100 psi at lower elevations near the Delaware River Canal. There is a possibility in those circumstances to intrude contaminated surface water into the distribution system (LeChevallier 1998). Because sources of perchlorate are not readily obvious at this location, additional monitoring and transport studies are warranted.

The presence of perchlorate in the Yardley well of Pennsylvania-American Water Company can also be possibly related to several contaminated sites located in the area which have been shown to caused groundwater contamination. *Moyers Landfill Superfund Site, 20 mi E of Yardley*, operated from 1940 to 1981. The 44-acre Moyers Landfill accepted an unknown quantity of municipal, sewage, and industrial wastes. Solid and liquid hazardous wastes thought to have included polychlorinated biphenyls (PCBs), solvents, paints, low-level radioactive wastes, and incinerated materials were disposed of at the landfill site. Off-site ground water, leachates, and soil are contaminated with heavy metals and volatile organic compounds from former waste disposal practices. *Naval Air Development Center, 9 mi E of Yardley*. site, which covers 840 acres and is located in Warminster generated waste during aircraft maintenance and repair, pest control, firefighting training, machine and plating shop operations, spray painting, and various materials research and testing activities in laboratories. Ground water both on-site and off-site is contaminated *North Penn Area, 15 mi E of Yardley*, located in Hatfield, Montgomery County, Pennsylvania, is a 350-acre area with volatile organic compound contamination in the ground water. Several industrial facilities are suspected of being sources of this contamination and are currently under investigation.

Synthetic organic contaminants such as trichloethylene (TCE) and tetrachloroethylene (PCE) have been detected in several San Marino Wells (CA), Monterey well (CA), Yardley (PA) and several Clovis (NM) wells (< MCL). In addition, Clovis wells have ben tested positive for trichloroethane (~1500 μg/L), dichloroethylene (~500 μg/L), Atrazine and Propazine (~2.0 μg/L). San Marino wells have high levels of nitrate. Elevated levels of barium were detected in the Marlin, IN wells (~ 200 μg/L). Barium could be associated with perchlorate as barium perchlorate. Organics such TCE and PCE are solvents employed in aircraft industry and also associated with operations where perchlorate is used. The perchlorate contamination in California sites also is in a TCE plume associated with past operations of propulsion companies (CDHS, 1997). Investigation of the hydrology of San Marino area indicated that contamination plumes are down gradient with the well off. Other synthetic organic contaminants which are also indirectly associated with the use of

explosives detected in San Marino wells are:1,3-Dimethyl-2-Nitrogen, Triphenyl Phosphate, and Perylene-D12 (<7.0 μg/L).

Although the sources are in the proximity of contaminated source waters, no actual testing has been done to confirm the movement of perchlorate to the water sources tested. But some groundwater contours examined do pass through these supposedly contaminated sites and may be related to the movement of contamination from the sites suggested in Table 2 and Figure 1. Figure 2 summarizes the various pathways through which perchlorate can reach drinking water sources.

Seasonal variation. It is highly possible to see seasonal changes in concentrations as the transport of perchlorate is temperature dependent and expected to be highest during summer months. This may lead to higher exposure to this chemical during summer months. Samples collected at two different times in Iowa (01/20/98; 02/25/98), Indiana (02/03/98; 03/30/98), and Pennsylvania (02/25/98; 02/09/98) produced different results (Table 2). The samples collected during the month of January/February tested positive and the samples tested during the month of February/March generally tested negative. This leads to the suggestion that perchlorate leaching and its transport from the contaminated site may be dependent upon rainfall and/or temperature. The variation in perchlorate levels could also be due to variations in analytical methodology. Samples collected from Clovis, New Mexico (01/12/98; 03/02/98) produced positive results during both testings. San Marino, CA (02/17/98) and LaSalle, CA (01/05/98) samples were collected only once and tested positive. Samples analyzed on a continuous basis in California for six months by the California Department of Health apparently showed no significant change in concentrations (Okamoto, 98; Lancaster, 98). Information gathered to investigate why there was no seasonal variation in California samples indicated that analytical methodology was not consistent throughout and there was not a significant variation in temperature during the sampling interval.

The transport of perchlorate from the contaminated site to source waters is dependent upon rainfall, distance from contaminated plume, type of soil, and temperature. For example, in the San Gabriel Valley, the soil is very sandy and permeable. The perchlorate, which does not bind to the soil appreciably and thus moves quickly with groundwater flows, apparently has migrated 15 miles away to the La Puente Valley Water District (The Sacramento Bee, 1998).

SOURCE CONTROL OF CONTAMINATION

Further large-scale contamination can be minimized by physically removing perchlorate waste and stabilizing with impervious and inert material to further stop its transport into the water sources. Perchlorate is a chemically inert compound which is difficult to neutralize and stabilize with other chemicals but can be made immobilized by mixing with concrete or by vitrification. Incineration of contaminated soil can also be employed to convert perchlorates to chlorides. This method produces toxic hydrochloric acid in the gaseous stream which must be captured and disposed off. Phyto-remediation and constructed wetlands are a low-cost alternative for decontamination of wastewater and soil containing high concentration of perchlorate (www.ibcusa.com/phyto). If an appropriate plant
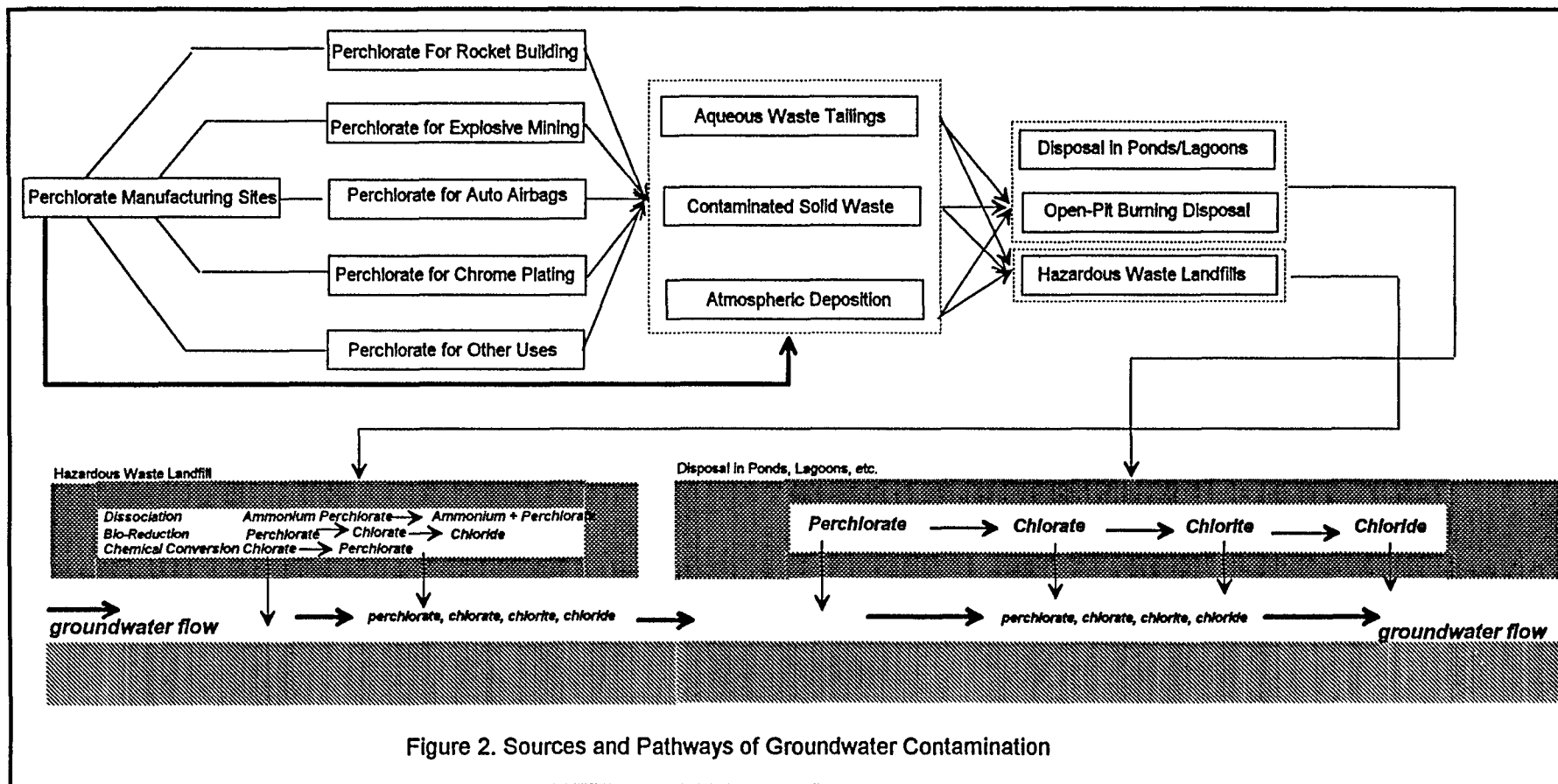
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Figure 2. Sources and Pathways of Groundwater Contamination

species can be found, the intensive use of this plant in a lined constructive wetland of several acres in surface area and large holding capacity has the potential to increase throughput and reduce holding time resulting in significant cost savings. An acceptable solution should be low maintenance, low energy coupled with low start-up costs.

CONTROL AND REMOVAL TECHNOLOGIES

There are no known effective and economical treatment technologies for removing perchlorate ion from drinking water sources containing low concentrations of this contaminant. Only limited information on the removal of perchlorate is available, and this data addressed the treatment of wastewaters containing high concentration of perchlorates. It was the consensus of a team of experts that met at a special workshop on perchlorate that "at this time there is no proven removal process available at the low concentrations being found in drinking water" (AWWARF, 1997). Typical water treatment technologies such as ion exchange, air stripping, carbon adsorption and advanced oxidation, have not been evaluated and investigated in-depth for perchlorate removal from drinking water sources.

Granular Activated Carbon (GAC). Siddiqui et al. (1996) have demonstrated that inorganic ions such as bromate (BrO_3^-) can be reduced to bromide ion using selected activated carbons. HLA (1997) have demonstrated that perchlorate concentrations at two GAC treatment units located at the Valley County Water District Lante and Big Dalton wells suggest that perchlorate levels were reduced. GAC removed perchlorate only for about two weeks. After a two week time span, the perchlorate concentration in the effluent was same as the influent concentration. However, these data were not reproducible in subsequent events. It is imperative that the right type of GAC is employed for this type of removal (Siddiqui et al., 1996).

Perchlorate removal from GAC can occur in three different ways: 1) the direct adsorption onto GAC, 2) reduction to other oxychlorine species [$ClO_4^- \rightarrow ClO_3^- \rightarrow ClO_2^- \rightarrow ClO^- \rightarrow Cl^-$], and by 3) biochemical reduction by microorganisms found and thrive on GAC. If decreases in perchlorate concentration are due to adsorption, fresh carbon would provide the greatest removal. Carbon that has been in use for some time would provide less capacity for adsorption and reduction and the removal is primarily by bio-reduction. Siddiqui et al. (1997) have observed bromide ion removal by adsorption and bromate removal by adsorption followed by reduction to bromide. They emphasize that adsorption and reduction was possible only in few selected activated carbons from a number of samples evaluated. Similar removal mechanisms are expected for perchlorate.

A new technology which uses activated carbon *fibers* is worth examining. Activated carbon fibers are a new technology possessing relatively much higher surface area than conventional activated carbon and can be designed to remove or capture any size particles. These fibers are currently being manufactured in Japan and are expected to cost less than traditional activated carbon. Their regeneration is supposedly relatively easier.

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Ion Exchange Resins. Studies conducted by the Aerojet General Corporation, CA have reportedly found that ion exchange is ineffective in removing perchlorate at low levels (HLA, 1997). This is presumably due to competition from higher concentration of ions such as chloride and sulfate. There are significant operational difficulties associated with the employment of resins. Like membranes, perchlorate is not treated but merely conveyed to a waste concentrate that would be a waste disposal challenge.

Membrane Technology. Preliminary information available indicates that this treatment is not cost effective in removing perchlorate ion at low concentrations. This process creates a waste disposal challenge. The size of the perchlorate ion was found to be 3.4 Å ($1 Å = 10^{-10}$ m). Based on this size, nanofiltration which works for particle sizes over 10 Å, may not look promising. But in actuality, removal is possible since the actual ionic size is much smaller than the pseudo ionic size normally encountered in solutions which is based on ionic double layer surrounding the perchlorate molecules. Based on results of bromide ion removal (Br⁻) investigated by Siddiqui et al. (1997), it is estimated that 30-60% of perchlorate can be removed using nanofiltration membranes with pore size of 300-400 Daltons. The associated operational problems include pretreatment of influent, use of anti-fouling agents, and membrane recovery by appropriate cleaning techniques.

Chemical Precipitation/Reduction. Removal of perchlorate by chemical conversions requires a reducing agent to provide the electrons. HLA (1997) evaluated reduction of perchlorate using sodium sulfite, sodium bisulfite, and sodium thiosulfate and at concentrations up to 1000 mg/L to water containing 7.0 mg/L perchlorate. Perchlorate concentrations did not significantly decrease over time. Although it is difficult to evaluate these methods in the absence of actual operating conditions, the removal efficiencies are expected to be much smaller at lower concentrations of perchlorate, normally encountered in drinking water sources. Siddiqui et al., (1994) has demonstrated that inorganic species such as bromate ion can be effectively reduced by employing a reductant such as ferrous sulfate. Siddiqui and Amy (1997) have also shown that bromate and bromide ions can be removed by adsorbing onto positive flocs of lime, alum, and ferric chloride. Perchlorate can also possibly be adsorbed onto the surface of alumina and silica gel particles.

Bio-treatment. Attaway and Smith (1993) and Wallace et al. (1996) have demonstrated that a mixed bacterial culture is capable of reducing perchlorate stoichiometrically to chloride under anaerobic conditions. Unfortunately, drinking water sources contain very low levels of perchlorate and application of this bio-technology is not feasible. The use of bio-filters or biological GAC filters currently employed in drinking water industry to reduced biodegradable organic compounds may be a possibility. Armstrong Laboratories use a biological process on their effluent (Armstrong Lab, 1997). Their residence time is 8 hours, and a flow rate of 5000 gpd. They are currently trying to apply this process for larger scale treatment. Merely lowering the E_h of the water to the range below -200 mV does not produce abiotic perchlorate reduction (Bliven 1996).

Low level perchlorate treatment is being conducted at the San Gabriel superfund site (CA) for the Baldwin Park Operable unit. This superfund site has been studied for several years; its focus being groundwater contaminated with synthetic organic compounds and heavy metals (HLA, 1997).

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High Energy Electron Beam Irradiation. This approach has shown promise to remove inorganic ions such as bromate, chlorate and organic compounds such as trihalomethanes (Siddiqui et al., 1996; Cooper et al., 1994). In view of this perchlorate is also expected to be converted to chloride ion and the removal is dependant upon the concentration of perchlorate ion. At low concentrations this method may not be feasible, but integration with other removal methods may be cost effective. Bromate destruction using a medium pressure mercury lamp is an alternative for decontamination of water containing perchlorate concentration in excess of 250 μg/L.

Capacitive Deionization with Carbon Aerogel Electrodes. Unlike ion exchange, one of the more conventional deionization processes, no chemicals are required for regeneration of the system (Farmer et al. 1996). Electricity is used instead. An aqueous solution of perchlorate ranging from 76 - 802 mg/L was pumped through the electrochemical cell and after polarization, perchlorate ions are removed from the water by the imposed electric field and trapped in the extensive cathodic and anodic double layers. This process produces one stream of purified water with concentration of perchlorate ranging from 32-690 mg/L and a second stream of concentrate. Unfortunately this method is neither effective nor applicable at lower concentrations normally found in drinking water sources.

A summary of methods available for perchlorate removal from drinking water sources is summarized in Table 3. Table 4 contains internet resources on perchlorate.

CONCLUSIONS AND RECOMMENDATIONS

■ Perchlorate is not a regulated compound under Safe Drinking Water Act, therefore currently there are limited data available regarding its occurrence. No comprehensive occurrence data is available for surface waters. A seasonal variation and occurrence data for both surface and ground source waters is needed since perchlorate's mobility in aqueous phase is temperature dependant.

■ Recent detection of perchlorate in several surface waters and ground water wells used to supply drinking water has created an unforseen water contamination crisis in the Western states, although problems are likely to emerge at other sites where perchlorate is used. Subsequent monitoring of 232 groundwater wells in California indicated perchlorate was in 69 wells (30%) and at concentrations above the action level in 20 wells (9%) (CDHS, 1997; AWWARF 1997). Samples taken from the Las Vegas Wash, which feeds Lake Mead and then the Colorado River, contained 1,500 to 1,680 μg/L (Urbansky 1997). The Los Angeles Metropolitan Water District measured 8 ppb in water at its intake in Lake Mead, and the Southern Nevada Water Authority found 11 ppb in its tap water.

■ Of the total 386 samples collected and analyzed from American Water System's ground water sources from several states and a diverse set of locations, only ten tested positive for perchlorate. The perchlorate concentrations ranged from <4 to 6 μg/L, well within the guideline value of 18 μg/L, suggested by California Department of Health.

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Table 3. Comparative Evaluation of Various Alternatives for Perchlorate Control

Technology	Comments	Final Products	Reference
Adsorption	■ Carbon Specific ■ Creates Concentrated Stream ■ Removes Other Contaminants	ClO_4^-, ClO_3^-, ClO_2^-, ClO^-, Cl^-	HLA, 1997 Siddiqui et al., 1995
Ion Exchange	■ Competition From Other Ions ■ NOM Masking ■ Disposal of Perchlorate	None	HLA, 1997 www.tc.thiokol.com
Chemical Reduction	■ pH Dependant ■ Not Effective - Low Levels ■ Adds New Contamination	Cl^-	HLA, 1997
UV Irradiation	■ Concentration Dependant ■ Water Quality Dependant ■ Removal of other pollutants	ClO_4^-, ClO_3^-, ClO_2^-, ClO^-, Cl^-	Siddiqui et al., 1996
Electron Beam	■ Adds No New Pollutants ■ Other - Same as UV	ClO_4^-, ClO_3^-, ClO_2^-, ClO^-, Cl^-	Siddiqui et al., 1996
Bio-Reduction	■ Biological Activated Carbon	ClO_4^-, ClO_3^-, ClO_2^-, ClO^-, Cl^-	tc.thiokol.com
Phyto Remediation	■ Only for source control ■ Inapplicable -Drinking Water	None	ibcusa.com/phyto

Table 4. Internet Resources on Perchlorate

ORGANIZATION	INFORMATION AVAILABLE	INTERNET ADDRESS
WCAS Laboratories, CA	Analytical Method	www.wcaslab.com/TECH/AZIDE.HTM
Wright-Patterson AFB	Risk Assessment/Removal Processes	www.wpgate1.wpafb.af.mil
Tyndall Air Force Base	Removal Investigations	www.aleq.tyndall.af.mil
Toxicology Excellence for Risk Assessment	Risk Assessment	www.tera.org/dataface/bin
Brooks AFB	Removal Processes	www.brooks.af.mil/HSC/AL/EQ/prod13.html
LA Review-Journal	Occurrence in Nevada	www.lvrj.com/lvrj_home/1997/Sep-07-Sun-1997/opinion/6009982.html
Pomona Council on Perchlorate, CA	General Information	www.intranet.csupomona.edu/~jhwei/perchlorate/index.html
Thiokol Corporation	Bio-Remediation	www.tc.thiokol.com http://www.engr.psu.edu/ce/Faculty/Perchlor.htm
Air Force Civil Engineers Group	Removal Success Stories	www.afcesa.af.mil/AFCESA/CE-Magazine-Fal/story21.htm
California Department of Health	Occurrence of Perchlorate in CA	www.dhs.cahwnet.gov
Phillips Laboratory	Reclamation of Perchlorate	www.plk.af.mil/SUCCESS/amm-perc.html

- The presence of perchlorate in drinking water sources is not a widespread problem but rather a localized issue. The data indicates it is associated with ordnance facilities and perchlorate manufacturing facilities. Perchlorate is used in solid rocket propellants, and has been found in areas where aerospace materials such as rocket fuel, fireworks, and munitions were manufactured and tested.

- It is imperative that control measures be in place to further stop the spread of contamination. Source control of perchlorate using removal and disposal of contaminated soil/water, incineration, phytoremediation, and constructed wetlands is a long lasting cost-effective solution to perchlorate intrusion into drinking water sources.

- Treatment methods effective for the removal of other pollutants are ineffective in the treatment and removal of perchlorate from the water supply. As discoveries of perchlorate grow in number, the urgency to discover a safe and efficient system of removal is imperative. The need for treatability studies to address the feasibility of perchlorate treatment at high flow rates and low concentrations exist.

- Recent improvements in analytical procedures allow identification of low concentrations of perchlorate in groundwater and surface water supplies. The current detection limit for this compound using ion chromatography method is 4 $\mu g/L$.

- A better understanding of perchlorate toxicity may help refine risk assessment and arrive a cleanup goal for drinking water sources that is both cost effective and provides an adequate margin of safety for all potential users.

- Several AWCs have no formal wellhead protection programs in place. Such guidelines include coordination with State program, monitoring of activities on Company-owned property surrounding the wellhead, and an assessment of the need to acquire additional property around the well so as to exercise control of activity within the area of influence of the well.

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OCCURRENCE OF METHYL TERTIARY BUTYL ETHER (MTBE) IN DRINKING WATER SOURCES

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ABSTRACT

A total of 2120 samples representing 450 wells (raw and treated) were tested from 16 states during 1997. Only 44 samples (~2%) tested positive for methyl tertiary butyl ether (MTBE), representing 17 wells (~ 4%), and the highest concentration (8.0 μg/L) was well below the EPA health advisory recommendation of 20-40 μg/L. Of these 44 samples, 22 were raw water, 21 treated water and one was from a distribution system. The main sources of MTBE contamination are underground storage tanks, pipelines, and spills. As of the end of 1997, there have been over 340,000 confirmed releases from underground storage tanks in the U.S. MTBE and other gasoline constituents have also been detected in several lakes and reservoirs across the country, with the source of MTBE thought to be release from recreational boating. Preliminary results have indicated that GAC filtration and air stripping remove MTBE in the range of 27-55%, with the removal efficiency a function of the initial MTBE concentration. The application of these technologies as a combination treatment is expected to enhance the removal of MTBE from contaminated sources.

Key Words - MTBE, ground water, occurrence

INTRODUCTION

Methyl tert-butyl ether (MTBE) has been used since the mid-1970s as a fuel additive, first in concentrations of 3% to boost octane, and more recently in concentrations of 13-15% to reduce carbon monoxide (CO) emissions and to promote complete burning. Additionally, the Clean Air Act (CAA) Amendments of 1990 mandate the use of oxygenates in gasoline, either seasonally (i.e. oxygenated gasoline) or year-round (i.e. reformulated gasoline), in specific areas of the United States where concentrations of carbon monoxide in the winter, or ozone in the summer, exceed established air-quality standards. Currently, 32 areas in 18 states sell reformulated gasoline. Reformulated gasoline accounts for about 30% of the gasoline sold nationwide, and MTBE is used in about 84% of the reformulated gas. In 1995, 8.0 billion kilograms of MTBE was produced in the United States, and between 1984 and 1994 the amount of MTBE production has increased by about 26 percent annually (Schirmer et al., 1997; Rodriguez et al., 1997; Daly et al., 1996). Essentially all of the MTBE produced or imported in the United States is used in the oxygenation of gasoline.

REGULATORY IMPETUS

As of 1998, methyl tertiary-butyl ether (MTBE) is not a regulated contaminant under the Safe Drinking Water Act (SDWA). However, United States Environmental Protection Agency (USEPA) has issued a health advisory (based on tastes and odors) for drinking water at 20 to 40 μg/L (USEPA, 1997), the California Department of Health Services has established a state action level at 18 μg/L, and the New Jersey Department of Environmental Protection has established an MCL of 70 μg/L. As a result of state legislation, California is required to establish a secondary standard for taste and odor for MTBE by July 1998 and a primary (health effects) standard by July 1999. According to the USEPA, (1997), there is little likelihood that MTBE concentrations of 20 to 40 μg/L in drinking water would cause adverse human health effects because the margin of exposure is about 10 to 100 times greater than would be provided by an EPA reference dose for non-cancer effects. An advisory does not mandate a standard for action (USEPA, 1998).

BACKGROUND

Releases from poorly managed and damaged underground storage tanks (USTs) are considered to be the main sources of localized MTBE contamination of groundwater sources. Buscheck et al. (1998) have reported detection of MTBE in over 83% of the UST sites, with about 45% of all sites having concentrations in excess of 1,000 μg/L. The highest frequencies of detection occurred at sites of currently operating stations in MD and TX (>90%), followed by CA (>80%) and FL (>70%). MTBE, and other oxygenates, were some of the 88 synthetic organic compounds (SOCs) measured as part of the USGS National Water-Quality Assessment Program in 1997 in US surface and ground waters. MTBE was included in the list of compounds measured because of its: (a) widespread use as an oxygenate, (b) potential for release from storage tanks and other point sources, (c) detection in shallow ground water in urban areas, and (d) impact to some drinking water wells.

Urban Groundwater. Contamination of individual wells in urban areas from leaking petroleum storage tanks poses unique problems for regulatory agencies, utilities, and responsible users. Of all the urban wells and springs sampled, 3% contained MTBE levels in excess of 20 μg/L. Of the 2,600 sites sampled for MTBE in California, 13 sources (<1%) contained detectable concentrations (MDL~5 μg/L) (CDHS, 1998). In Denver, 79 percent of the shallow urban wells had detectable concentrations of MTBE (MDL~0.2 μg/L). In urban areas within Connecticut, Massachusetts and Vermont, 37 percent of the wells had detectable MTBE concentrations. By contrast, only 1.3 percent of the wells sampled in 20 agricultural areas had detectable concentrations of MTBE. MTBE was detected only in agricultural areas in southern Colo., New England, and eastern Pennsylvania. On average, 27 percent of shallow urban wells had detectable concentrations of MTBE. MTBE was detected in shallow ground water in: Denver, Colo., New England, Reno, Nev., Albany, N.Y., Dallas/Ft. Worth, Texas, Las Vegas, Nev., Atlanta, Ga., and Albuquerque, N.M.

Storm water. The detection of MTBE in about 7% of 592 storm water samples from several states with concentrations ranging from <0.2 to 8.0 μg/L is an indication of atmospheric washout

(Squillace et al., 1996). MTBE was detected in some urban storm water samples collected in 16 cities and metropolitan areas by the USGS, but all detections of MTBE were less than the lower limit of the draft health advisory for drinking water. At a reporting level of 1.0 μg/L for most samples, MTBE was detected in one or more storm water samples in eight cities--Atlanta, Baton Rouge, Birmingham, Colorado Springs, Denver, Dallas/Fort Worth, San Antonio, and Phoenix. The detection rate in urban storm water was highest in samples collected during the months of October through March each year of the study (1991-1995). This October-March period corresponded with the expected seasonal use of oxygenated gasoline. Of 62 synthetic organic compounds (SOCs) measured in 592 storm water samples collected in 16 cities in 11 states, all with populations greater than 100,000, MTBE was the seventh most frequently detected SOC being detected in 41 of the 592 storm water samples. In decreasing order, the most frequently detected SOCs were toluene, total xylenes, chloroform, trimethyl benzene, tetrachloroethene, and napthalene. Concentrations of MTBE ranged from 0.2 to 8.7 μg/L with a median of 1.5 μg/L.

Ground water. At a reporting level of 0.2 μg/L, MTBE was detected in 22% of 304 shallow monitoring wells sampled in 13 urban areas. MTBE was detected in less than 3% of shallow wells in agricultural areas or deeper wells in major aquifers. MTBE was the second most frequently detected volatile organic compound (VOC; of 60 compounds measured) in urban areas. About 2% of the shallow urban wells exceeded 20 μg/L MTBE. However, none of these wells were used as a source of drinking water. In contrast, none of the concentrations in agricultural areas or deeper wells exceeded 20 μg/L. MTBE varied substantially among the 13 urban areas investigated. Urban areas where MTBE was most commonly detected include Denver (79% of wells), Harrisburg, PA (37%), and various cities in New England (37%). Urban areas where MTBE was not detected include Ocala and Tampa, FL, Portland, OR, and Virginia Beach, VA. Possible sources of MTBE in ground water include point sources, such as leaking storage tanks, and nonpoint sources such as recharge of precipitation and stormwater runoff.

SOURCES OF MTBE

The main sources of MTBE contamination are underground storage tanks, pipelines, spills, contaminated sites, and MTBE manufacturing and storage sites. As of the end of 1997, there have been over 340,000 confirmed releases from underground storage tanks in the U.S. (USEPA, 1998). MTBE and other gasoline constituents have been detected in several lakes and reservoirs across the country. The primary source of MTBE presence in urban surface waters is release from recreational boating and air deposition through precipitation of industrial or vehicular emissions. Atmospheric deposition in major cities where MTBE is being used may result in a nonpoint source for the transport of MTBE into shallow groundwater. MTBE in urban air partitions into rain at quantifiable levels (Pankow, 1997). USGS data collected from 1993-1994 show the highest concentrations of MTBE in shallow groundwater in urban areas of Denver, New England, and Pennsylvania (USGS, 1995). MTBE accumulates in snow at sites such as service stations, parking lots, streets and may eventually leach into water sources. MTBE can also be released from wastewater treatment operations at petroleum operations and publicly owned treatment facilities. The potential sources of MTBE and their pathways are summarized in Figure 1.

Some MTBE is lost through photochemical reactions

Atmosphere

Volatilization from waste, unit processes and storage

Volatilization and Leakage during transport

Refilling and Refueling Operations

- Leakage
- Volatilization
- Exhaust

MTBE Manufacture ➞ UST ➞ Automobiles

- Waste disposal
- Storage Leaks

- Industrial users
- Discharge into landfills
- Illegal Dumping

- Leaking tanks
- Contamination and seepage

- Rain washout
- snow washout

SOIL

See Figure 2 for MTBE decomposition pathways

MTBE and its decomposition byproducts

Gelogic rocks below water table

Figure 1. Sources and Pathways for Groundwater Contamination

PHYSICAL AND CHEMICAL CHARACTERISTICS

MTBE is a volatile, organic compound and may constitute up to 15% (v/v) of the gasoline mixture. The drinking water contamination is most likely a consequence of MTBE's small molecular size and relatively high water solubility (~ 5,000 mg/L water) which permits it to readily migrate through water sources (Stephenson et al., 1992; Mackey et al., 1993). Reformulated gasoline is about 50 times more soluble in water than conventional gasoline due to the fact that reformulated gasoline consists of about 10-15% MTBE. When MTBE leaks to ground water, it spreads both farther and faster than the gasoline, and the concentration of gasoline dissolved in ground water increases (Garrett et al., 1986). Because of its relatively low Henry's Law constant (~0.002; dimensionless), MTBE partitions readily from air to rainfall and snowfall (log K_{oc}~0.8; log K_{ow}~1.0)(Mackey et al., 1993; Ames, 1995; Squillace et al., 1992). Additionally, because of low Henry's Law constant, air stripping is less effective for MTBE removal than other VOCs normally encountered in groundwater, because air stripping of trace organic compounds depends on volatilization as removal mechanism. The greater the Henry's coefficient, the greater the driving force for transfer of the solute from the aqueous to the gas phase.

Synthetic organic compounds normally detected in groundwater have octanol:water partition coefficients in the range of 200 to 1,000 (log K_{ow} ~2 to 3). Hence, they may be regarded as moderately hydrophobic, and therefore tend to partition into other phases such as air. This partitioning tendency is important for treatment, because it largely determines the driving force for processes such as air stripping and adsorption. MTBE which has K_{ow} ~1 is not as susceptible to stripping as trichloroethylene (TCE), which has K_{ow} of 2.3.

MTBE TRANSPORT AND MODELING

MTBE is polar, has low soil exchange capacity, and is expected to be more mobile than BTEX (benzene, toluene, ethylene, xylene) compounds. The transport of MTBE is governed by its retardation factor, a function of its relative velocity of movement, which can be obtained from the following equation:

$$\frac{1}{u_r} = [1 + (6.3 \times 10^- \rho_s f_{oc} \frac{K_{ow}}{\varepsilon})]$$

where u_r = relative velocity of movement of a concentration front of MTBE compared to the velocity of movement of a front of a conservative tracer; ρ_s = density of soil, 2 x 10^6 g/m^3; f_{oc}=fraction of organic carbon in soil. The above equation can also be written as:

$$\frac{1}{u_r} = \frac{v_{tracer}}{v_{solute}} = [1 + 6.3 f_{oc} K_{ow}]$$

5

This model equation can be used to estimate the transport of solutes such as MTBE whose octanol:water partition behavior is known in an aquifer with known organic content. For example, in an aquifer containing 1% organic carbon, TCE (K_{ow} =199) will be retarded by a factor of 13, whereas MTBE (K_{ow}=10) will be retarded by a factor of less than 2. Clearly, MTBE can be expected to migrate much more rapidly and farther than TCE in the subsurface environment and there is a strong prospect that a weak sorbing solute such as MTBE will be encountered much farther from its source.

The Hydrocarbon Spill Screening Model (HSSM) model was developed by the U.S. Environmental Protection Agency to serve as a simplified model for subsurface releases of fuel hydrocarbons. The model is most commonly used to address the problem of a leaking underground storage tank. The model tracks the flow of the water-immiscible fuel, simulates the dissolution of various chemicals (BTEX or MTBE) into ground water, and calculates the transport of contaminants to receptors in aquifers. The New Jersey's Department of Environmental Protection advection/dispersion model for MTBE is similar to HSSM model but takes into account the transport of selected MTBE decomposition products (e.g., tert-Butyl Alcohol).

HEALTH RISKS AND TOXICITY OF MTBE

There are many uncertainties and limitations associated with the toxicity for this chemical. The animal tests conducted to date were not conducted by exposing the animals to MTBE in drinking water, but rather by inhalation exposure. Although useful for identifying potential hazards, limitations of the reported studies do not allow confident estimates of the degree of risk MTBE may pose to humans from low-level drinking water contamination.

A study was performed to determine whether the acute toxicities to representative species from the Baltic Sea of blended fuels containing methanol or methyl tertiary butyl ether differed from those of base fuel, gasoline or low leaded gasoline (Tarkpen and Svanberg, 1982). *Alburnus alburnus* (bleak) and the harpacticoid *Nitocra spinipes* were chosen as representative species. Low leaded gasoline, base fuel and blend fuel M15 15% methanol were rather highly acute toxic to the bleak. Of the three additives methanol , isobutanol and MTBE, the first was practically non-toxic, while isobutanol and MTBE were slightly toxic. Sub-lethal effects such as disturbed balance, surface swimming and overturning were noted in the bleak after only a couple of minutes of exposure to MTBE. Several individuals recovered before the experiment was ended. The 96 hour median lethal dose values for *Nitocra spinipes* varied between about 150 and 250 mg/liter for the actual motor fuels. For the bleak, the toxicity of the three additives was less than that of the actual motor fuels. The results of the study demonstrate that the acute toxicity of base fuel to aquatic organisms was not increased by the addition of 15% methanol or 5% MTBE. The risk of increasing the toxicity by the use of solvents with the potency of dissolving more of the hydrocarbons into the water phase was not verified in the experiment.

DECOMPOSITION AND DEGRADATION OF MTBE

MTBE degradation occurs through both biotic and abiotic transformation processes. Abiotic processes include dehydrogenation, hydrolysis, oxidation/reduction, and photolysis (Shelley et al., 1994; Church et al., 1998; Davidson et al., 1995; Hubbard et al., 1994; Pankow et al., 1992; Rixey et al., 1994; Squillace et al., 1996; Schirmer et al., 1997; Smith et al., 1991; Ribbons et al., 1972). Biotic transformation processes include biochemical oxidation, biodegradation, biotransformation, and metabolic transformation (Yeh et al., 1995; Salamitro et al., 1992; Yeh et al., 1994; McMahon et al., 1995; Novak et al., 1992). MTBE can be removed during transport in water by several processes such as absorption, adsorption, air-water/transfer exchange, bioaccumulation, degradation, sorption to humic materials and sediments (Wibowo, 1994; Mackay et al., 1993; Speth et al., 1990; Borden et al., 1997; Bianchi et al., 1989; ITC, 1988)

Several research studies have indicated that the biodegradation of MTBE is slow and takes several days (Church et al., 1988; Yeh et al., 1994; McMahon et al., 1995). Analysis of water samples from six well sites by Church et al. (1988) did not produce any evidence of in-situ degradation of MTBE. However, effluent from a column microcosm prepared with core material from an urban site showed conversion of MTBE to tert-butyl alcohol (TBA). In surface waters, soils, and ground waters, the likely expected pathways for MTBE degradation are microbially mediated hydrolysis and oxidation (Wallenfels, 1967; Ribbons et al., 1972). The major product of both pathways is TBA. The likely degradation products for MTBE are summarized in Figure 2.

SAMPLING AND ANALYTICAL PROCEDURES

Samples from water sources were collected in 40 mL amber vials with no head space and with minimal mixing to minimize volatilization of MTBE. Sample vials contained ascorbic acid (40 mg/L) and 1+1 hydrochlorous acid (2-3 drops). Samples were shipped in insulated containers containing blue ice by overnight delivery. The samples were analyzed within the 14 day holding period.

The conventional purge-and-trap method (EPA 524.2) GC/MS method was used to analyze all the samples for MTBE. This method has excellent agreement with newer procedures described by Church et al. (1998) that can detect the major alkyl ether compounds that are used as gasoline oxygenates and characteristic degradation products in water at <1 μg/L concentrations. This new method involves the use of a gas chromatograph with direct aqueous injection onto a polar column via splitless injector, coupled with detection by mass spectroscopy. The method can also give simultaneous identification of polar products that might occur as degradation products of gasoline. Standard EPA method 502.2 using a GC/PID can also be applied, but false positives are expected because of co-eluting constituents.

RESULTS AND DISCUSSION

The American Water System began measuring MBTE in January 1997 as part of its routine
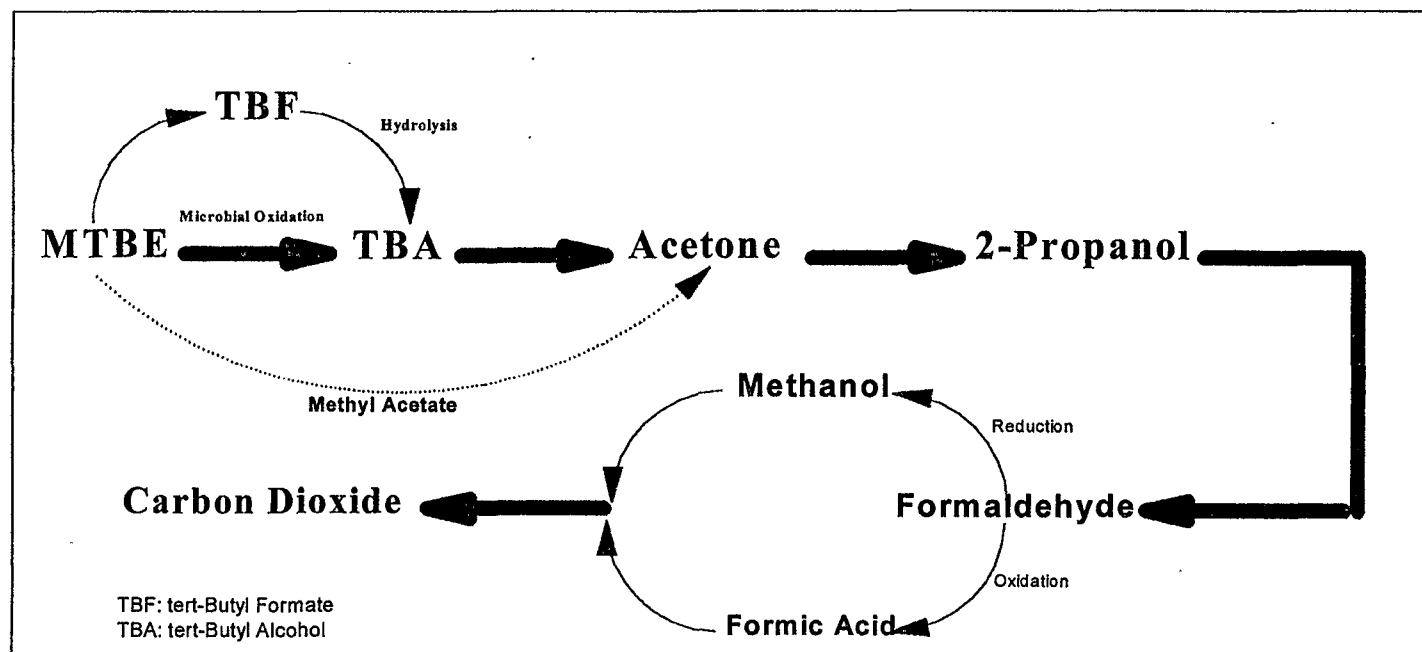
Figure 2. Proposed Biodegradation Byproducts of MTBE

groundwater VOC monitoring. A total of 2120 samples representing 450 wells (raw and treated) were tested from 16 states during 1997. Only 44 samples (~2%) tested positive for MTBE, which originated from 17 wells (~ 4%). All samples were below the EPA advisory's recommendation of 20 μg/L, with the highest concentration observed at 8.0 μg/L MTBE. Of the 44 samples, 22 were raw water, 21 treated water, and one was from a distribution system. A list of sites tested positive is summarized in Table 1 and portrayed graphically in Figure 3. These states are required to use MTBE to improve combustion and to reduce carbon monoxide emissions. The state of New Jersey had the highest number of sites tested positive for MTBE. Incidentally, a large number of groundwater sources in that state have tested positive for other contaminants as well, most notably TCE. Squillace et al. (1996) have also reported a correlation between the presence of MTBE and other contaminants such as benzene, chloroform, and other BTEX compounds.

As of the end of 1997, there have been over 340,000 confirmed releases from underground storage tanks in the U.S. (USEPA, 1998). The number of underground leaking tanks in the vicinity of sites tested in the state of New Jersey has been summarized in Table 2 and the specific UST sources responsible for contamination are listed in Tables 3 and 4 . This Table supports the notion that USTs are a major problem for groundwater MTBE contamination. The sources other than USTs which may contribute to MTBE contamination and located in the vicinity of source waters are briefly described below:

New York Systems. Raw water from Bedford Village Park area contained MTBE at a concentration of 0.6 μg/L. The company purchases water from the Connecticut-American Water company. Raw water from a series of reservoirs is treated at the Putnam filtration plant prior to delivery to the New York-American system. Several contaminated areas in the proximity of Bedford were located. The reservoirs could be the source of atmospheric MTBE deposition. Katonah contaminated site and a Brewster's Superfund site were located in the vicinity of Bedford. These sites have contaminated groundwater with various VOCs. The Katonah Municipal Well site [3 mi N] is located on a peninsula that extends into the Muscoot Reservoir, which supplies drinking water to New York City. In addition, the area surrounding the well and pump house had been historically used for the disposal of street cleaning debris. The street sediments, debris and other waste can easily contain deposited MTBE and this can leach into groundwater. Volatile organic compounds (VOCs) were discovered in the Village of Brewster Well Field's water distribution system in 1978 [10 mi N). Subsequent testing revealed a large plume of ground water contamination due to a variety of illegal waste dumping.

Massachusetts Systems. Oak Pond Station, Millbury, contained MTBE at a concentration of 1.1 μg/L. The Oak Pond gravel packed well is only 30 ft deep and is controlled by the water level in the Burbank reservoir. The treatment involves only chlorination and the addition of caustic. The MTBE contamination is suspected to be from the reservoir and contamination through storm water flow and infiltration.

West Virginia Systems. A well from Minden area contained MTBE at 2.3 μg/L. The raw water is supplied from two abandoned coal mines. The primary source is Minden mine. Three wells

Table 1. Occurrence of MTBE in Groundwater and their Suspected non-UST Sources

NUMBER	LOCATION	STATE	TYPE	MTBE, μg/L	# SAMPLES	POSSIBLE NON-UST SOURCES^	OTHER SUSPECTS^
1	Monmouth	NJ	RAW	1.0-3.3	2	✓ Naval Ammunition Depot (5 mi N)~ ✓ Freehold & Asbury Sitesl (<5 mi R)·	✓ USTs
2	Delaware Valley	NJ	RAW	0.5-1.2	5	✓ Numerous contaminated sites	✓ Unkept wells ✓ Shallow aquifers ✓ Fuel tanks kept underground
3	Delaware Valley	NJ	EFF	0.5-8.0	12	--	✓ Influence of surface water ✓ Storm water, USTs
4	Lakewood	NJ	RAW	0.6	1	✓ McGuire Air Force Base (10 mi W) ✓ Naval Air Station (5 mi W)~ ✓ Ammunition Depot (10 mi N)~	✓ USTs
5	Fire Road	NJ	RAW	0.8-7.5	13	✓ Delilah Road Site (<3 mi R)· ✓ Federal Aviation Admin. Site (5 mi E)~ ✓ Price Landfill (< 1 mi E)~	✓ Several USTs in the vicinity
6	Fire Road	NJ	EFF	0.6-2.4	7	--	✓ Petroleum products in vicinity
7	Shore	NJ	RAW	2.2-2.9	2	✓ Industrial contaminated sites	✓ USTs ✓ Influence of surface water
8	Shore	NJ	EFF	1.7-2.0	2	--	✓ From raw water
9	Greenwich	CT	RAW	0.8	1	✓ Katonah Site (10 mi N)~	✓ USTs
10	Greenwich	CT	EFF	0.6	1	--	✓ From raw water
11	Mystic	CT	EFF	0.5	1	✓ New London Submarine Base (2 mi E)~	✓ Permeable soil ✓ Shallow Aquifers
12	Millbury	MA	EFF	1.3	1	✓ Fort Deven (15 mi E)~ ✓ Westborough Site (4 mi E)~	✓ Burban Reservoir ✓ Shallow aquifer (<30 ft)
13	Coronado	CA	DIST	1.0	1	✓ Naval Air Station (<1 mi)~ ✓ Storm Water Runoff	✓ Colorado River ✓ Delata-SPW water
14	Bedford	NY	RAW	0.6	1	✓ Katonah Well Site (3 mi N)· ✓ Brewster Superfund Site (10 mi N) ·	✓ Infiltration during transport ✓ Atmospheric washout
15	Minden	WV	RAW	2.3	1	✓ Storm Water Wash (?)	✓ Coal mines located

~ These sites have tested positive for BTEX compounds such as benzene normally associated with gasoline.
· These non-UST sources are speculative and no actual testing has been done to confirm these sources. This information is listed to provide guidance to future monitoring programs

Note: For detailed NJ locations see Figure 2

Figure 3. MTBE Occurrence in American Ground Water Systems

BTEX Compounds indicative of gasoline contamination also detected in Belevidere, Camden, Atlantic City, Delaware Valley
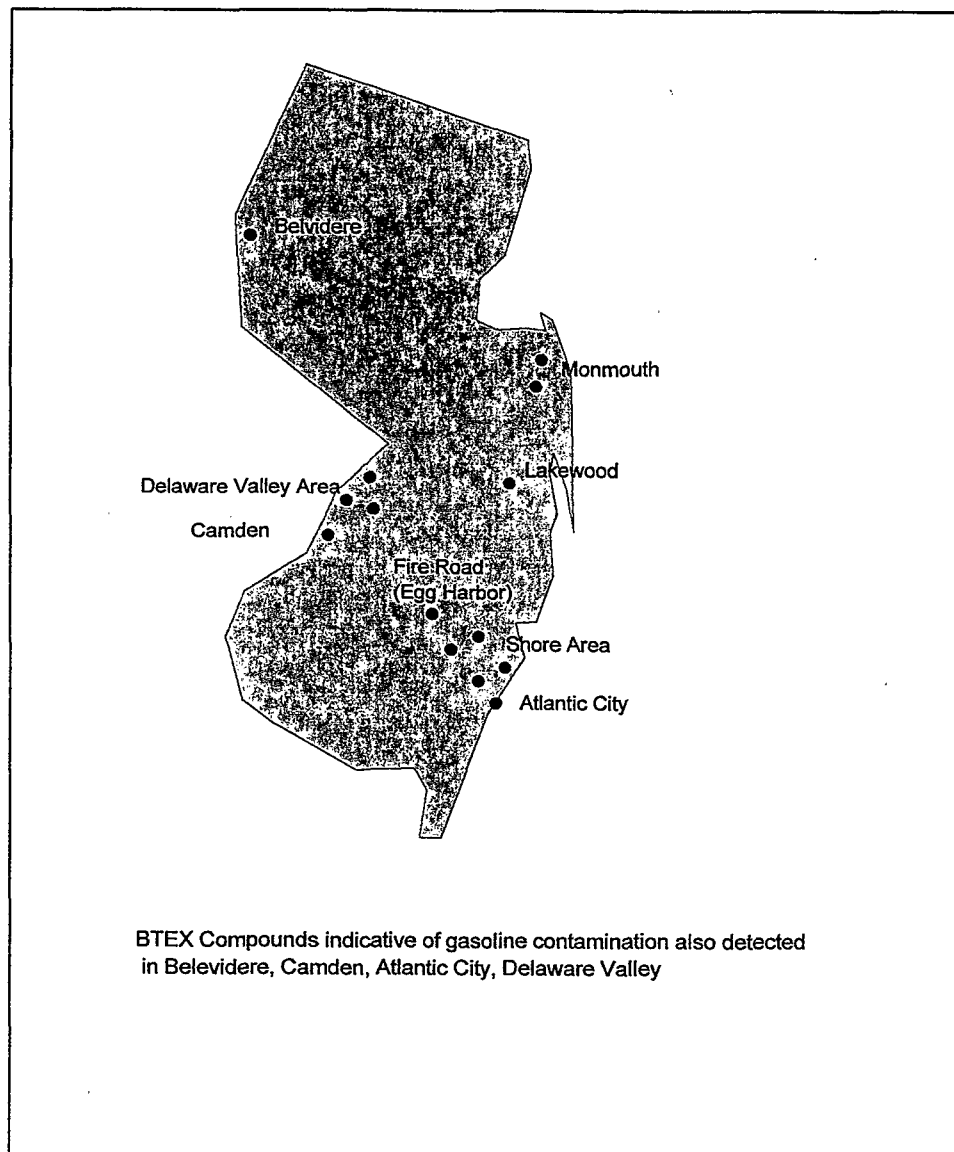
Figure 4. NJ-AWC Sites Tested Positive for MTBE

Table 2. Locations of Leaking USTs in New Jersey

LOCATION	# USTs LEAKING	STATUS
Salem County	150	40 - NFA 110 - ATP/AA
Cumberland County	255	82 - NFA 173 - ATP/AA
Cape May County	252	96 - NFA 156 - ATP/AA
Atlantic City	110	42-NFA 68-ATP/AA
Egg Harbor City	54	20 - NFA 34 - ATP/AA
Fire Road. Egg Harbor	7	4 - NFA 3 - ATP/AA
Monmouth County	940	400-NFA 540 - ATP/AA
Monmouth Beach	4	3 - NFA 1 - ATP/AA
Lakewood	1	NFA

ATP - assigned for a program;
NFA - no further action needed;
AA - awaiting action

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Table 3. Leaking USTs in the Vicinity of Fire Road/Egg Harbor/Monmouth Sampling Wells^

COUNTY	CITY	LOCATION	SOURCE
Atlantic	Egg Harbor	3173 Fire Road	Fortune Gypsum*
Atlantic	Egg Harbor	2515 Fire Road	Martys*
Atlantic	Absecon	rt 30 4 Shore Rd	Amoco*
Atlantic	Bargaintown	Adams & Baushore	Brigantine Pump Station*
Atlantic	Mullica	1141 Tilton Rd	Blazer Station*
Atlantic	Northfield	E Mill Rd	Former EXXON*
Atlantic	Northfield	1121 New Rd	Gulf Service Station*
Atlantic	Northfield	Rte 9 and Mill Rd	Mill Rd School*
Atlantic	Northfield	775 W Mill Rd	City Public Works*
Atlantic	Pleasantville	Delilah 5& Mill	McDonnel Truck*
Atlantic	Pleasantville	Delilah & Mill	SK Associates*
Atlantic	Somers Pt.	Shore Rd & NY	Memorial Hospital*
Atlantic	Somers Pt.	668 New Rd	Coastal Service Station*
Atlantic	Egg Harbor	Fire & Delilah Rd	Pleasantville*
Atlantic	Egg Harbor	Fire and Tilton	MOBIL*
Atlantic	Egg Harbor	Fire and Tilton	SUNOCO*
Atlantic	Egg Harbor	Fire and Railroad	Sussman Car Dealer*
Atlantic	Egg Harbor	3162 Fire Road	Szathmary Supply*
Monmouth	Lakewood	23 S Congress St	23 S Congress*

^ Although the sources are in the proximity of the tested wells, no actual testing has been done to confirm the movement of MTBE to the water sources. These potential sites are listed to aid further studies.

* New Jersey Department of Environmental Protection (NJDEP, 1998

Table 4. Leaking USTs in the DELAWARE VALLEY distribution area

COUNTY	CITY	FACILITY	ADDRESS	STATUS
Burlington	BEVERLY	BERNHEIM SIEGEL CORP	630 BROAD ST	BAC
Burlington	BEVERLY	CLOSED EXXON STATION	BROAD & WARREN ST	AA
Burlington	BEVERLY	EXXON SERVICE STATION	BROAD ST & WARREN ST	AA
Burlington	BURLINGTON	AMOCO S/S	RTE 130 & HIGH ST	NFA-A
Burlington	BURLINGTON	AMOCO SERVICE STATION #60750	RTE 130 & HIGH ST	NFA-A
Burlington	BURLINGTON	AUERBACH CHEVROLET	RTE 130	BAC
Burlington	BURLINGTON	AUERBACH CHEVROLET CORP	RTE 130 S	ATP
Burlington	BURLINGTON	BURLINGTON BRISTOL BRIDGE FACILITY	CONOVER ST	ATP
Burlington	BURLINGTON	BURLINGTON CENTRAL OFFICE (NJB)	446 HIGH ST	NFA-A
Burlington	BURLINGTON	BURLINGTON CITY DEPARTMENT	MITCHELL & FEDERAL	ATP
Burlington	BURLINGTON	BURLINGTON CITY SEWAGE	WEST BROAD STREET	CMS
Burlington	BURLINGTON	BURLINGTON CITY WASTEWATER TREATME	W BROAD ST	NFA-A
Burlington	BURLINGTON	BURLINGTON CITY WATER TREATMENT PL	E PEARL ST	NFA-A
Burlington	BURLINGTON	BURLINGTON POST OFFICE	427 HIGH ST	NFA-A
Burlington	BURLINGTON	BURLINGTON TOWNSHIP HIGH SCHOOL	6 PENN FOUNTAIN AVE	NFA-A
Burlington	BURLINGTON	BURLINGTON TOWNSHIP MUNICIPAL BUIL	851 OLD YORK RD	NFA-A
Burlington	BURLINGTON	BURLINGTON TOWNSHIP MUNICIPAL CENT	851 OLD YORK RD	NFA-A
Burlington	BURLINGTON	BURLINGTON WORK CENTER	9 ELBOW LN	NFA-A
Burlington	BURLINGTON	CHATEAU APARTMENTS	SUNSET RD	NFA-A
Burlington	BURLINGTON	CITGO SERVICE STATION	RTE 541	AA
Burlington	BURLINGTON	CUMBERLAND ARMS APTS	RT 541	NFA-A
Burlington	BURLINGTON	DELAWARE PETROLEUM	RTE 130	ATP
Burlington	BURLINGTON	EXXON S/S	SUNSET & SALEM RD	NFA-A
Burlington	BURLINGTON	EXXON S/S #3-6013	1 KEIM BLVD	ATP
Burlington	BURLINGTON	EXXON SERVICE STATION	2503 MT HOLLY BURLINGT	NFA-A
Burlington	BURLINGTON	EXXON SERVICE STATION #3-5143	2218 MT HOLLY RD	ATP
Burlington	BURLINGTON	FARKAS AUTO BODY	1202 RTE 130 N	AA
Burlington	BURLINGTON	FORMER TEXACO-BURLINGTON GAS & DIERT	130 & WOOD ST	ATP
Burlington	BURLINGTON	GULF SERVICE STATION #126313	2212 MT HOLLY RD	AA
Burlington	BURLINGTON	HENKELS AND MCCOY INCORPORATED	512 ELBOW LN	NFA-A
Burlington	BURLINGTON	HERCULES INC	300 NECK RD	NFA-A
Burlington	BURLINGTON	HESS STATION #30319	2201 MT HOLLY RD	ATP
Burlington	BURLINGTON	IN AREA OF OLIVE ST	JACKSONVILLE RD	AA
Burlington	BURLINGTON	KMART #3077	1817 MT HOLLY RD	NFA-A
Burlington	BURLINGTON	LESTER FELLOWS TRUCKING	EAST PEARL AND LATHAM	NFA-A
Burlington	BURLINGTON	LIQUID CARBONIC CORP	NECK RD/DULTY LN	NFA-A
Burlington	BURLINGTON	MASONIC HOME & CHARITY FOUNDATION	902 JACKSONVILLE RD	NFA-A
Burlington	BURLINGTON	MASONIC HOME OF NJ	902 JACKSONVILLE RD	NFA-A
Burlington	BURLINGTON	MCCOLLISTERS MOVING & STORAGE	1800 N RTE 130	CMS
Burlington	BURLINGTON	MCCOLLISTER'S MOVING & STORAGE	LOGAN & MITCHELL AVE	NFA-A
Burlington	BURLINGTON	OCCIDENTAL CHEMICAL NORTH PLANT	1804 RIVER RD	NFA-A
Burlington	BURLINGTON	OCCIDENTIAL CHEMICAL	BEVERLY RD	NFA-A
Burlington	BURLINGTON	PARAM PETRO SERVICE STATION	RTE 130 & WOOD ST	NFA-A
Burlington	BURLINGTON	PARKVIEW MOBIL	RT 130 & COLUMBUS RD	ATP
Burlington	BURLINGTON	PEH BURLINGTON	RTE 130 & PRINCETON	ATP
Burlington	BURLINGTON	PROSOURCE DISTRIBUTION CENTER	600 COMMERCE DR	AA
Burlington	BURLINGTON	PROSOURCE DISTRIBUTION SVCS	600 COMMERCE DR	NFA-A
Burlington	BURLINGTON	PSE&G BURLINGTON GENERATING STATIO	WEST BROAD ST & DEVLIN	NFA-A

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Burlington	BURLINGTON	ROLAND WILLIS JR & SON INC;	WILLIS1011 RTE 130 S	ATP
Burlington	BURLINGTON	SADOWSKI PROPERTY	221 E RTE 130	NFA-A
Burlington	BURLINGTON	SEARS ROEBUCK & COMPANY	RTE 541 BURLINGTON CE	NFA-A
Burlington	BURLINGTON	SHELL SERVICE STATION	MT HOLLY & SUNSET RDS	ATP
Burlington	BURLINGTON	SPORT DODGE	2000 RTE 130 S	NFA-A
Burlington	BURLINGTON	SUNOCO SERVICE STATION (FORMER) #0	RTE 130 & MOTT AVE	ATP
Burlington	BURLINGTON	TOOLEY'S GARAGE INCORPORATED	STEVEN STATION & NEC	NFA-A
Burlington	BURLINGTON	CITY AVERBACH CHEVY	RTE 130 S & LAWRENCE S	NFA-A
Burlington	BURLINGTON	CITY CAPTAIN JAMES LAWRENCE SCHOOL	BROAD ST	NFA-A
Burlington	BURLINGTON	CITY CECCHI PARTNERSHIP	415 SAINT MARY ST	ATP
Burlington	BURLINGTON	CITY FLORENCE LIQUOR MART	291 RTE 130	NFA-A
Burlington	BURLINGTON	CITY PRICE BUILDING SUPPLY INC	444 LOGAN AVE	NFA-A
Burlington	BURLINGTON	CITY SADOWSKI PROPERTY	221 E HWY 130 & POST	AA
Burlington	BURLINGTON	CITY SADOWSKI PROPERTY	221 RT 130	NFA-A
Burlington	BURLINGTON	CITY US PIPE AND FOUNDRY	EAST PEARL STREET	NFA-A
Burlington	BURLINGTON	WHITESELL ENTERPRISES	1817 RTE 130	ATP
Burlington	CINNAMINSON	AFG INDUSTRIES	2600 RIVER RD	NFA-A
Burlington	CINNAMINSON	ALTOS EXPRESS INCORPORATED	2301 GARRY RD	NFA-A
Burlington	CINNAMINSON	ARTHUR J EVERS CORPORATION	1009 BROAD ST	AA
Burlington	CINNAMINSON	BARONE'S SERVICE CENTER INC	RTE 130 & HIGHLAND AVE	ATP
Burlington	CINNAMINSON	BLUE LANTERN MOTEL	208 N RTE 130	NFA-A
Burlington	CINNAMINSON	CINNAMINSON DPW	1601 UNION LANDING RD	CMS
Burlington	CINNAMINSON	CINNAMINSON HIGH SCHOOL	RIVERTON RD	ATP
Burlington	CINNAMINSON	CINNAMINSON POLICE DEPARTMENT	900 MANOR RD	NFA-A
Burlington	CINNAMINSON	CINNAMINSON TWP	1621 RIVERTON RD	NFA-A
Burlington	CINNAMINSON	CINNAMINSON UHAUL	US HWY RT 130	AA
Burlington	CINNAMINSON	CINNIMINSON TOWNSHIP HIGH SCHOOL	RIVERTON RD	NFA-A
Burlington	CINNAMINSON	DERINGERS PETERBILT INC/EASY AUTO	2701 & 2703 RIVER RD	ATP
Burlington	CINNAMINSON	DNA PLANT	2611 BRANCH PIKE	NFA-A
Burlington	CINNAMINSON	EXXON	1706 HIGHLAND AVE	BFO
Burlington	CINNAMINSON	EXXON SERVICE STATION	RTE 130 & CHURCH RD	NFA-A
Burlington	CINNAMINSON	EXXON SERVICE STATION #3-8358	RT 130 & HIGHLAND AVE	NFA-A
Burlington	CINNAMINSON	EXXON SERVICE STATION #3-9790	RTE 130 & CINNAMINSON	NFA-A
Burlington	CINNAMINSON	GBC INDUSTRIAL	2611 RIVER RD	NFA-A
Burlington	CINNAMINSON	MOBIL S/S 15-ECH	RT 130 & WILLOW RD	ATP
Burlington	CINNAMINSON	MOBIL SERVICE STATION #15-DH6	RTE 130/RIVERTON	ATP
Burlington	CINNAMINSON	MOBIL SERVICE STATION CINNAMINSON	CHURCH RD & RTE 130	ATP
Burlington	CINNAMINSON	NEW PENN MOTOR EXPRESS INC		NFA-A

^ Although the sources are in the proximity of the tested wells, no actual testing has been done to confirm the movement of MTBE to the water sources. These potential sites are listed to aid further studies.

have been drilled 500 ft into the shaft of the mines. The plant uses caustic soda for coagulation and sedimentation and employs no aeration or GAC treatment. The mines receive heavy runoff from surrounding areas during rainfall. Infiltration of MTBE into the wells is suspected since diffusion through soil is unlikely in view of the considerable depth of these wells.

California Systems. A well in Coronado tested positive and contained MTBE at 1.0 μg/L. Cal-Am serves the four cities of Coronado, Imperial Beach, south Chula Vista, and parts of south San Diego. There are several U.S. naval installations adjoining the service territory which may have contributed to the MTBE occurrence. The Camp Pendleton Marine Corps Base site covers 125,000 acres in San Diego County, California. Past disposal practices have contaminated the groundwater and soil with fuel waste and other contaminants. The base contains wetlands, streams, and rivers, which feed into the Pacific Ocean. Groundwater and soils are contaminated with volatile organic compounds (VOCs), spent oils, fuels, polychlorinated biphenyls (PCBs), pesticides, metals and herbicides..

New Jersey Systems. A number of sites in the Delaware Valley, Fire Road Operating Center, Lakewood, and Monmouth service areas tested positive for MTBE. Several hundred leaking USTs are located in the vicinity of these areas (Table 4; Figure 4) that may have contributed to MTBE in groundwater (NJDEP, 1998). Inaddition, there are several non-UST contaminated sites in the vicinity of tested sources which have contributed to other episodes of groundwater contamination (Figure 5). Several of these sites have tested positive for BTEX compounds present in gasoline. The identification of these sites is intended to aid in future studies of MTBE transport in groundwater.

Fire Road Operating Center. Several leaking USTs are located in the vicinity of Fire Road, Mill Road, New Road, Tilton Road, Shore Road, Dobbs Avenue Station, Woodland Station, and at almost all other places where the distribution system is laid out. The other suspected sources are briefly discussed below: The 40 acre *Delilah Road site* accepted municipal and household wastes from 1974 to 1980, but records indicate that drummed flammable wastes and sludges containing VOCs were dumped at the site. Numerous incidents of illegal dumping were reported after the site was closed. The *Federal Aviation Administration* (FAA) Center site borders the Garden State Parkway in southeastern New Jersey. Jet fuel has contaminated soil and groundwater at this area. Contaminants of concern include volatile organic compounds (VOCs) such as benzene. To date, approximately 35,000 gallons of jet fuel product have been extracted and sent off-site for treatment, and approximately 75 million gallons of groundwater have been treated on-site. The 26 acre *Price Landfill* site is located in Egg Harbor Township. During its operation, it is estimated that over 9 million gallons of chemical waste were disposed of at the site. Groundwater is contaminated with volatile organic compounds (VOCs) including gasoline component benzene.

Lakewood. Lakewood distribution system pumps water from 5 wells from the English aquifer at depths of 580-768 ft, one well pumps water from the lower aquifer, in the Raritan formation from a depth of 1697 ft, and 4 wells pump water from the Kirkwood-Cohansey aquifer from a depth of 85 ft. The Englishtown and lower Raritan aquifers have been identified as threatened with contamination or depleted. Because the Kirkwood-Cohansey aquifer is an unconfined and relatively shallow aquifer, these wells could be susceptible to contamination from

Finalized Sites: 119

· Proposed Sites: 121

Construction Completed Sites: 32
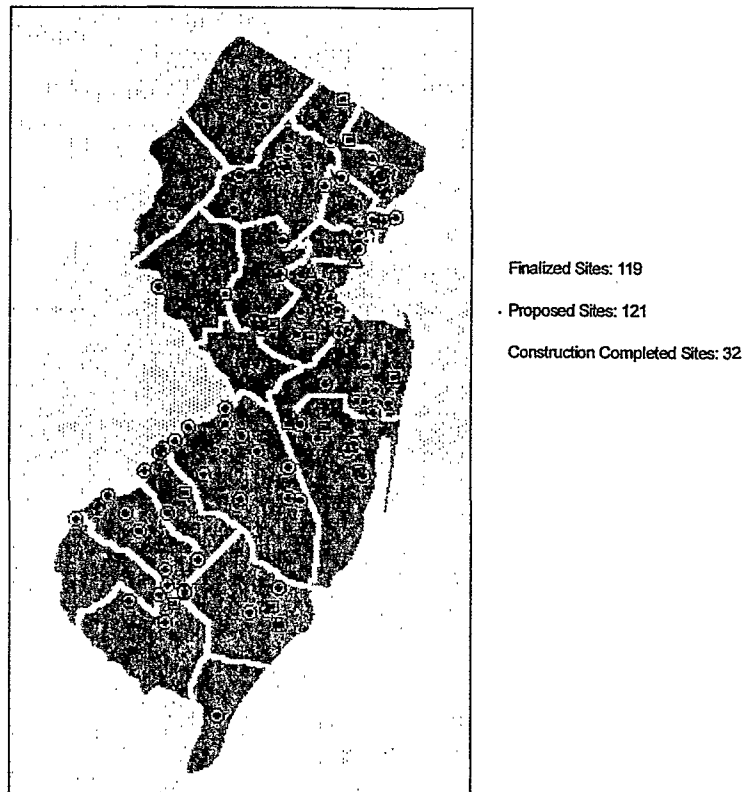
Figure 5. Sites in NJ Responsible for Groundwater Contamination (USEPA, 1998)

USTs. Neither air stripping nor GAC filtration is employed for these source waters and no removal is expected during iron oxidation or clarification.

Delaware Valley. NJWC Delaware Valley service area is supplied by 17 wells screened in the Raritan formation. Wells, located at the Highland Avenue Station, Beverly Station, and Ivy Road, were found to contain low levels of MTBE. The wells located at the Highland Area were also contaminated with TCE. NJWC stored gasoline and diesel fuel in underground tanks located at Highland Avenue, Morgan Avenue, and Office/DC from 1980 to 1990 (CPS, 1987). The Highland plant uses GAC contactors with an EBCT of 15 min. The combined flows from wells 15, 16, 32 at the Beverly station discharge to an air stripping unit. Water from the Ivy road wells is pumped directly into the distribution system after treatment with caustic, phosphate and chlorine and involves no air stripping/GAC. Water from other areas of the Delaware valley is not treated by air stripping and GAC. The wells in Beverly location are relatively shallow (57 ft deep) compared with the Ivy (123 ft) and Highland avenue (198 ft) wells and could be susceptible to contamination from USTs.

Monmouth Area. Only 5% of the water in this area is served by ground water wells. The wells are located in the city of Aberdeen and are 375-409 ft deep. The Aberdeen plant derives water from 4 wells and is fed through 2 vertical feed tray type aerators, each with a capacity of

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3000 cfm. The aerated water then flows into a flash mix basin where chlorine is added. There are numerous leaking USTs located in the proximity of these wells.

Connecticut Systems. Groundwater in the cities of Mystic and Greenwich measured MTBE ranging from 0.5 to 0.8 μg/L. The Noroton district's only source of water supply, the Rewak Well, is located off Lake Drive in Darien, CT, and includes an air stripping treatment facility constructed in 1983. The town has primarily remained residential with a relatively small number of business and commercial, but no industrial establishments.

The Mystic Valley District has two groundwater production wells. The Lantern Hill Well treatment facility, which has a rated capacity of 1.0 mgd, was constructed in 1969 and consists of three continuous regeneration filters. Copps Brook well is located on the upper reaches of Copps Brook and is used only during drought periods. Water pumped from this well is discharged into a small tributary stream of Copps Brook which feeds the Dean's Mill reservoir. The city of Mystic is located close to the London Submarine base and the water in Greenwich is in the proximity of Katonah contaminated site, which is located very close to Bedford, NY. The New London Submarine Base covers 1,412 acres on the east bank of the Thames River. Volatile organic compounds, pesticides, PCBs, spent battery acids, and other waste were buried below the water table in the 25-acre Landfill, located on base wetlands. Ground water in some areas is as shallow as 10 feet below the surface, and soils are permeable.

In addition to the possible sources listed above, the likelihood that MTBE contamination could occur during sample collect should be examined. Because of the high solubility of MTBE in water, it is possible that if gasoline containers or fumes were present at the time of sample collection, low levels of MTBE might result as a contaminant. Inclusion of trip blanks in addition to typical negative samples could evaluate this route of contamination. In this case the trip blanks should be opened and transferred to empty vials a the same time the water samples are collected.

EVALUATION OF REMOVAL TECHNOLOGIES

Removal strategies for MTBE from drinking water sources involves air stripping, adsorption onto activated carbon, and oxidation. Ground water contaminated with MTBE is difficult to remediate. Filtration through activated carbon is not cost effective for MTBE: a 2 cubic foot bed lasts a month or less as a household treatment system, even with an influent concentration of MTBE as low as a few parts per billion (Garrett et al., 1986). However , air stripping systems are capable of removing MTBE, but only if very high air-to-water ratios are used ($\geq$200:1). The presence of MTBE in spilled gasoline increases dissolved concentrations of gasoline in ground water in the immediate vicinity of the spill by an order of magnitude above typical values for spills in which there is no MTBE present. MTBE is more difficult to remove from contaminated water than the other components of gasoline.

Granular Activated Carbon and Air Stripping. Granular activated carbon (GAC) adsorption has long been the state of the art for point-of-entry (POE) treatment of private household water supplies contaminated with petroleum products such as gasoline and various fuel oils (Lowry et al., 1988). Results indicate POE systems using aeration followed by GAC are a viable, cost-effective, short-term solutions while groundwater remediation is performed or an alternate drinking water supply is secured. Selection and design of the POE system should

consider variations in water usage and contaminant concentrations. The presence of iron or manganese did not affect the POE system performance at the ten sites studied. However, iron precipitation was observed and may pose problems in some POE applications. Increased concentrations of non purgeable dissolved organic carbon consisting primarily of MTBE and hydrophilic petroleum hydrocarbons were found in the raw waters but did not affect volatile organic chemical (VOC) removals by aeration or GAC. Microbial activity as measured by heterotrophic plate count significantly increased in four of the ten POE systems studied. The reliability of POE systems is achieved by specifying top quality system components, educating POE users, providing routine maintenance, and VOC monitoring.

The inability of GAC to effectively treat groundwater containing high levels of MTBE has created a need for an effective alternative to these POE applications. A diffused aeration system employing multiple stages in series, was found to be ideally suited to the treatment of gasoline contaminated household water supplies at 3 sites in Maine (Lowry et al., 1988). The diffused aeration process is capable of treating water containing several hundred mg/L of total gasoline to drinking water quality. Diffused aeration is more cost effective than granular activated carbon treatment, especially for highly contaminated water supplies. MTBE was the controlling compound for the design and operation of the aeration process. It was the most difficult volatile organic carbon to strip, and resulted in aeration volume and energy requirement of approximately twice that required for benzene and toluene. The capital cost of a commercial aeration system is approximately 50% higher than a typical 2-unit GAC installation with softening or other forms of iron pretreatment. When MTBE is present in significant concentrations, or petroleum contamination in high concentrations, GAC and aeration are not very comparable since GAC is incapable of economically removing the contamination. The operational cost of GAC due to frequent bed replacement in these applications makes aeration the only cost effective alternative.

A new technology which uses activated carbon *fibers* is worth examining. Activated carbon fibers are a new technology possessing a much higher surface area than conventional activated carbon and can be designed to remove or capture any size particles. These fibers are currently being manufactured in Japan and are expected to cost less than traditional activated carbon. Their regeneration is reportedly easier.

Table 5 summarizes the effect of passive removal processes the removal of MTBE. The efficiency of removal is a function of the initial MTBE concentration.

Ozone-Peroxide Oxidation. Ozone (~2-3 mg/L) in combination with low concentration of hydrogen peroxide (~0.5-1.5 mg/L) can potentially convert MTBE to less polar and more biodegradable organic compounds. Oxidation reduces the MTBE to byproducts such as methanol, formaldehyde, formic acid, tert-butyl formate, tert-amyl alcohol, methy acetate, acetone and acetaldehyde. All of these compounds are more easily biodegradable than MTBE and do not cause the taste and odor problems associated with MTBE. Application of biological filtration following oxidation may be required to control biological growth due to the conversion of MTBE to more biodegradable products.

Comparative Evaluation. Table 6 summarizes the comparative evaluation of air stripping, GAC, ozone oxidation, and biological filtration for MTBE removal. Both activated carbon adsorption and air stripping are options for treating groundwater containing dissolved

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Table 5. MTBE Control strategies

Location	State	Capacity mgd	Initial MTBE $\mu g/L$	Aeration/GAC Treatment	% Removal
Lakewood	NJ	3.2	0.6	None	
Delaware Valley	NJ	7.0	0.6-1.1	✓ Aeration ✓ GAC	27-45
Monmouth	NJ	38.5	1-3.3	✓ Aeration ✓ GAC	45-55~
Fire Road	NJ	??	0.6-7.7	None	
Shore	NJ	??	2.2-2.9	None	
Mystic	CT	1.4	0.5	✓ Anthracite Sand	0-12~
Greenwich	CT	16.5	0.8	✓ Air Stripping	40-50~
Minden	WV	??	2.3	None	
Bedford	NY	??	0.6	None	
Millbury	MA	1.6	·1.3	None	

~ estimated values based upon initial concentration and the optimum air-to-water ratio. Air-to-water ratio was calculated using the relationship [Air/Water = R. P/H] where H is Henry's Law Constant of MTBE (~0.083 atm-m³ water/m³ air), R is stripping factor (optimum value is ~3). The optimum ratio was calculated to be 36:1. Process train where no aeration was involved and removal was effected only by transport and longitudinal mixing, the stripping factor was assumed to be equal to one and the ratio was calculated to be equal to 12. From Figure 6, MTBE removal efficiencies for ratios 36 and 12 are 12% and 40%, respectively.

Table 6. Comparative Evaluation of Alternative Technologies for MTBE Removal

Treatment	Air Stripping	GAC Filtration	Ozone Oxidation	Bio-filtration
Effectiveness	✓ Has low Henry's constant ✓ Dependent on air-to-water ratio	✓ Limited adsorption capacity ✓ AC Fibers may be more effective	✓ Ozonation is less effective than ozone-peroxide oxidation	✓ Resistant to biodegradation ✓ Efficient if used in combination with oxidation
Treatment Cost	✓ Low to Moderate ✓ Treating off-gas would double the cost ✓ High operating cost and low capital cost	✓ Twice than air stripping ✓ Cheaper if other VOC removal required ✓ High Capital and low operating cost	✓ Slightly more expensive than GAC ✓ High capital and moderate operating cost	✓ Same as GAC
Advantages	✓ Removes other VOCs	✓ Removes other SOCs ✓ Air Stripping + GAC can increase GAC life	✓ Can treat other taste and odor problems	✓ Removes other growth-promoting compounds
Disadvantages	✓ Requires GAC or incineration as secondary containment to meet air emissions	✓ Concentrate disposal problem ✓ GAC regeneration required	✓ Bio-growth problem ✓ Byproducts formed ✓ Residual peroxide	✓ Slow ✓ Requires continuous monitoring
Operational Problems	✓ Scaling and freezing during cold seasons	✓ Requires breakthrough monitoring	✓ Requires optimum use of ozone	✓ Requires removal of disinfectants and oxidants

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gasoline components. For low-concentration low-volume applications, the cost differential between carbon adsorption and air stripping is likely to be low enough that a decision can be based on availability, ease of installation, and operation. For high-volume high-concentration applications, air stripping is the less expensive. option Carbon adsorption on a stand-alone basis may become more cost-effective if emission treatment is required in conjunction with the air stripping system. Treatment costs for carbon adsorption with non-destructive regeneration reflect high initial capital investment and low operating costs while treatment costs for air stripping generally reflect the opposite, especially at high air/water ratios. In areas where electrical costs are higher than average, air stripping and ozone oxidation may lose some of their cost advantage. Air stripping requires a minimum air/water ratio of 15 cfm/gpm to achieve 99.9% removal efficiency for methyl t-butyl ether. At a flow rate of 200 gpm, air stripping treatment cost is not a function of concentration and stripping gains a cost advantage over carbon adsorption as concentration increases. This conclusion assumes that the treatment goal for an air stripping system is 99.9% removal. If specification of an effluent concentration requires a removal efficiency >99.9%, the treatment cost for air stripping will be a function of concentration. Figure 6 gives a relationship between the removal efficiency and air-to-water ratio.
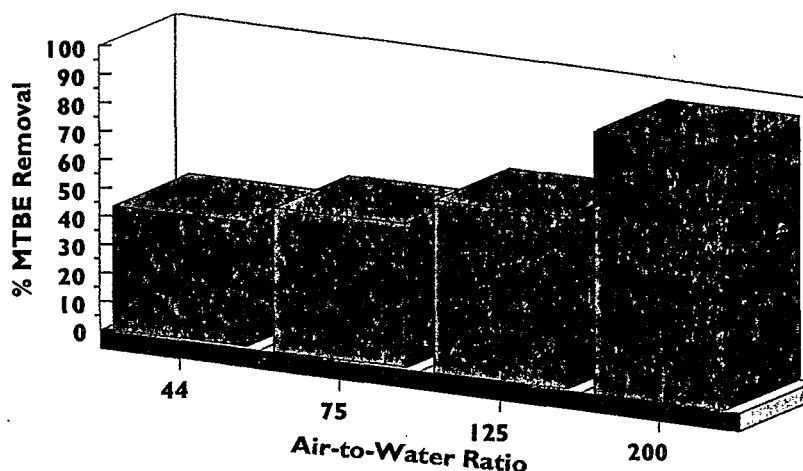
Figure 6. Removal of MTBE by Air Stripping (after McKinnon and Dyksen, 1984)

CONCLUSIONS AND RECOMMENDATIONS

■   There is paucity of information related to the removal of MTBE from drinking water sources. Technologies needed to be studied include oxidation, air stripping, activated carbon fibers, and bio-filtration. Air stripping is known to work but information on the efficacy of air stripping in combination with other processes such as GAC or bio-filtration is required.

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- MTBE contamination of groundwater should be considered to be a potentially nationwide problem and not just a localized or a coastal problem. Over a million USTs exist in the United States and many are in bad conditions and the potential to cause a widespread groundwater contamination problem is present.

- Biodegradation rates and pathways need to be studied to understand the fate of MTBE and its products, and to design cost-effective control strategies.

- The concentration of MTBE in groundwater sources may be expected to increase in the years to come as use of reformulated gasoline increases. It is imperative to monitor MTBE concentrations on a regular basis and improvements of treatment plants using ground waters should consider MTBE control strategies.

- To maximize MTBE removal from ground water sources, an optimum air-to-water ratio should be used and an effective carbon contact time established. For plants where air stripping alone is not effective, use of GAC or carbon fibers in combination with stripping should be considered.

- For MTBE-contaminated source waters where there is a chronic problem with taste and odor compounds, VOCs, or iron or manganese problems, the use of ozone should be evaluated as a cost-effective multiplicative strategy.

- The systems currently using GAC are not designed for MTBE removal. An optimization study should be performed to enhance the removal of MTBE along with other SOCs. The GAC contact time and the type of GAC is crucial to effectively remove SOCs and this should be kept in mind when choosing a new or replacing existing GAC filtration systems.

- Bench or pilot-scale studies should be performed to evaluate the decomposition of MTBE by ozone. A combination of ozone oxidation and biological filtration should be evaluated as a cost-effective integrated system to remove MTBE and other organic contaminants

- Any shallow ground water sources should be phased out or properly treated to reduce the potential for contamination.

- The use of activated carbon fibers should be evaluated for remove SOCs, and specifically, MTBE.

- Trip blanks should be included in sample kits for MTBE analysis to evaluate the impact of sample contamination by gasoline fumes at the time of sampling.

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APPENDIX I. List of VOCs Detected in Places Where MTBE was Tested Positive

METHYL TETRIARY BUTYL ETHER (MTBE)	2.4	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
CHLOROACET ONITRILE	0.8	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
TRICHLOROE THYLENE	1.2	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
TETRACHLOR OETHYLENE	7.7	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
1,1-DICHLOROET HANE	0.6	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
CHLOROFOR M	0.8	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
BENZENE	0.7	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
ACETONE	1.0	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
cis-1,2-DICHLOROET HYLENE	2.0	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02R MILL RD	RAW
CHLOROFOR M	0.5	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02E MILL RD	EFF
METHYL TETRIARY BUTYL ETHER (MTBE)	2.0	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02E MILL RD	EFF
TETRACHLOR OETHYLENE	0.8	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 02E MILL RD	EFF
1,1-DICHLOROET HANE	0.5	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 06R N LINWOOD	RAW
ACETONE	1.4	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 06R N LINWOOD	RAW
CHLOROFOR M	1.2	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 06R N LINWOOD	RAW
ACETONE	1.0	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 06E N LINWOOD	EFF
ACETONE	0.6	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 71E CONT A UPPER	EFF

CHLOROFOR M	0.9	106	FIRE ROAD	01/09/98	FIRE ROAD	NJS 71E CONT B UPPER	EFF	
NAPHTHALEN E	1.0	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	WINKLER'S FARM	RAW
ACETONE	1.8	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	WINKLER'S FARM	RAW
METHYL ETHYL KETONE	1.0	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	WINKLER'S FARM	RAW
NAPHTHALEN E	6.7	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RTE 22 SPILL SOUTH	RAW
METHYL ETHYL KETONE	0.9	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RTE 22 SPILL SOUTH	RAW
ACETONE	1.0	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RTE 22 SPILL SOUTH	RAW
1,2,4- TRIMETHYLBE NZENE	1.2	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RTE 22 SPILL SOUTH	RAW
1,2,4- TRIMETHYLBE NZENE	3.4	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RTE 22 SPILL NORTH	RAW
ACETONE	1.1	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RTE 22 SPILL NORTH	RAW
METHYL ETHYL KETONE	1.0	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RTE 22 SPILL NORTH	RAW
NAPHTHALEN E	10.0	108	NEW YORK AMERICAN WATER CO	01/09/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RTE 22 SPILL NORTH	RAW

BROMODICHL OROMETHAN E	3.0	535	CULLODEN DISTRICT	01/13/98	WEST VIRGINIA AMERICAN WATER CO	CULLODEN DISTRICT	PLANT	EFF
CHLOROFOR M	19.7	535	CULLODEN DISTRICT	01/13/98	WEST VIRGINIA AMERICAN WATER CO	CULLODEN DISTRICT	PLANT	EFF
TETRACHLOR OETHYLENE	0.6	103	DELAWARE VALLEY	01/13/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 10A	RAW
ACETONE	5.6	103	DELAWARE VALLEY	01/13/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 10A	RAW
ACETONE	0.8	103	DELAWARE VALLEY	01/13/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 10E	EFF
TETRACHLOR OETHYLENE	0.5	103	DELAWARE VALLEY	01/13/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 10E	EFF
1,1,1- TRICHLOROE THANE	4.1	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 12R	RAW
1,1- DICHLOROET HANE	1.3	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 12R	RAW
CHLOROFOR M	0.5	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 12R	RAW
TETRACHLOR OETHYLENE	4.2	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 12R	RAW
CHLOROFOR M	6.0	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 31R	RAW
TRICHLOROE THYLENE	0.8	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 31R	RAW
cis-1,2- DICHLOROET HYLENE	1.9	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 31R	RAW
1,1- DICHLOROET HANE	0.5	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 31R	RAW

METHYL TETRIARY BUTYL ETHER (MTBE)	0.9	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 31R	RAW
1,1,1-TRICHLOROETHANE	0.8	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 01E	EFF
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 01E	EFF
CHLOROFORM	2.9	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 01E	EFF
cis-1,2-DICHLOROETHYLENE	0.6	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 01E	EFF
METHYL TETRIARY BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 01E	EFF
TETRACHLOROETHYLENE	0.8	103	DELAWARE VALLEY	01/14/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 01E	EFF
2-BUTANONE (MEK)	0.6	108	NEW YORK AMERICAN WATER CO	01/14/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RT 22 -N	RAW
ACETONE	1.5	108	NEW YORK AMERICAN WATER CO	01/14/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	RT 22 -N	RAW
ACETONE	1.5	108	NEW YORK AMERICAN WATER CO	01/14/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	BEDFORD VILLAGE PARK	RAW
METHYL tert-BUTYL ETHER (MTBE)	0.6	108	NEW YORK AMERICAN WATER CO	01/14/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	BEDFORD VILLAGE PARK	RAW
2-BUTANONE (MEK)	0.5	108	NEW YORK AMERICAN WATER CO	01/14/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	MIANUS ROAD	RAW
ACETONE	1.1	108	NEW YORK AMERICAN WATER CO	01/14/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	MIANUS ROAD	RAW

ACETONE	2.0	108	NEW YORK AMERICAN WATER CO	01/14/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	335 GREENWICH RD	RAW
2-BUTANONE (MEK)	0.8	108	NEW YORK AMERICAN WATER CO	01/14/98	NEW YORK AMERICAN WATER COMPANY	25 WILLETT AVENUE	335 GREENWICH RD	RAW
ACETONE	8.6	209	MILLBURY DISTRICT	01/15/98	MASSACHUSETTS AMERICAN WATER CO	MILLBURY DISTRICT	OAK POND STATION	EFF
METHYL tert-BUTYL ETHER (MTBE)	1.1	209	MILLBURY DISTRICT	01/15/98	MASSACHUSETTS AMERICAN WATER CO	MILLBURY DISTRICT	OAK POND STATION	EFF
TETRACHLOROETHYLENE (PCE)	0.6	209	MILLBURY DISTRICT	01/15/98	MASSACHUSETTS AMERICAN WATER CO	MILLBURY DISTRICT	OAK POND STATION	EFF
CHLOROFORM	13.5	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW28E	EFF
BROMODICHLOROMETHANE	1.7	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW28E	EFF
ACETONE	1.3	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW28E	EFF
CHLOROFORM	0.7	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW67E	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW67E	EFF
ACETONE	0.9	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW67E	EFF
BROMODICHLOROMETHANE	10.1	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW36E	EFF
CHLOROFORM	12.3	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW36E	EFF
DIBROMOCHLOROMETHANE	7.6	110	MYSTIC DISTRICT	01/15/98	CONNECTICUT AMERICAN WATER Co	MYSTIC DISTRICT	CAW36E	EFF

METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 05R	RAW
TETRACHLOROETHYLENE (PCE)	9.2	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 05R	RAW
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 23E	EFF
1,1,1-TRICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 23E	EFF
1,1-DICHLOROETHANE	0.6	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 23E	EFF
CHLOROFORM	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 23E	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 1A	EFF
TETRACHLOROETHYLENE (PCE)	9.4	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 1A	EFF
TRICHLOROETHYLENE (TCE)	1.0	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 1A	EFF
1,1-DICHLOROETHANE	0.6	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 1B	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 1B	EFF
TETRACHLOROETHYLENE (PCE)	1.3	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 1B	EFF
TRICHLOROETHYLENE (TCE)	0.6	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 1B	EFF
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 1C	EFF
TRICHLOROETHYLENE (TCE)	0.9	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2A	EFF

1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2A	EFF
TETRACHLOROETHYLENE (PCE)	10.1	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2A	EFF
1,1-DICHLOROETHANE	0.6	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2B	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2B	EFF
TETRACHLOROETHYLENE (PCE)	2.0	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2B	EFF
TRICHLOROETHYLENE (TCE)	0.8	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2B	EFF
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2C	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 2C	EFF
TETRACHLOROETHYLENE (PCE)	9.0	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 3A	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 3A	EFF
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 3A	EFF
TRICHLOROETHYLENE (TCE)	1.2	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 3A	EFF
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 3B	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 3B	EFF
TRICHLOROETHYLENE (TCE)	0.8	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 3B	EFF

METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 3C	EFF
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4A	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4A	EFF
TETRACHLOROETHYLENE (PCE)	5.8	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4A	EFF
TRICHLOROETHYLENE (TCE)	1.2	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4A	EFF
1,1,1-TRICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4B	EFF
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4B	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4B	EFF
1,1,1-TRICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4C	EFF
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4C	EFF
METHYL tert-BUTYL ETHER (MTBE)	0.5	103	DELAWARE VALLEY	01/16/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 41 4C	EFF
TETRACHLOROETHYLENE (PCE)	12.9	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 04R	RAW
TRICHLOROETHYLENE (TCE)	4.7	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 04R	RAW
METHYL tert-BUTYL ETHER (MTBE)	1.4	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 04R	RAW
CHLOROFORM	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 04R	RAW

1,1-DICHLOROETHANE	2.4	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 04R	RAW
1,1,1-TRICHLOROETHANE	0.9	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 04R	RAW
TETRACHLOROETHYLENE (PCE)	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 10A	RAW
1,2,3-TRICHLOROPROPANE	1.3	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 33R	RAW
1,2-DICHLOROPROPANE	3.8	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 33R	RAW
TRICHLOROETHYLENE (TCE)	0.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 33R	RAW
1,1,1-TRICHLOROETHANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 35R	RAW
TETRACHLOROETHYLENE (PCE)	0.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 35R	RAW
TRICHLOROETHYLENE (TCE)	1.1	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 35R	RAW
1,2,3-TRICHLOROPROPANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 37E	EFF
1,2-DICHLOROPROPANE	1.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 37E	EFF
1,1,1-TRICHLOROETHANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 1A	EFF
TRICHLOROETHYLENE (TCE)	0.7	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 1A	EFF
1,1,1-TRICHLOROETHANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 1C	EFF
1,1,1-TRICHLOROETHANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 2A	EFF

TRICHLOROE THYLENE (TCE)	0.7	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 2A	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 2B	EFF
TRICHLOROE THYLENE (TCE)	0.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 2B	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 2C	EFF
1,1,1- TRICHLOROE THANE	0.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 3A	EFF
TRICHLOROE THYLENE (TCE)	0.9	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 3A	EFF
TRICHLOROE THYLENE (TCE)	0.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 3B	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 3B	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 3C	EFF
TRICHLOROE THYLENE (TCE)	0.9	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 4A	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 4A	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 4B	EFF
TRICHLOROE THYLENE (TCE)	0.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 4B	EFF
1,1,1- TRICHLOROE THANE	0.7	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 4C	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 5A	EFF

TRICHLOROE THYLENE (TCE)	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 5A	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 5B	EFF
1,1,1- TRICHLOROE THANE	0.7	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 5C	EFF
TRICHLOROE THYLENE (TCE)	1.0	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 6A	EFF
1,1,1- TRICHLOROE THANE	0.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 6A	EFF
TRICHLOROE THYLENE (TCE)	0.8	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 6B	EFF
1,1,1- TRICHLOROE THANE	0.6	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 6B	EFF
1,1,1- TRICHLOROE THANE	0.7	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 6C	EFF
TRICHLOROE THYLENE (TCE)	0.5	103	DELAWARE VALLEY	01/20/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 38 6C	EFF
CHLOROFOR M	0.7	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 04E	EFF
CHLOROFOR M	1.5	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 08E	EFF
METHYL tert- BUTYL ETHER (MTBE)	2.1	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02R	RAW
1,1- DICHLOROET HANE	0.6	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02R	RAW
TETRACHLOR OETHYLENE (PCE)	7.1	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02R	RAW
TRICHLOROE THYLENE (TCE)	1.1	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02R	RAW

BENZENE	0.6	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02R	RAW
CHLOROFORM	0.8	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02R	RAW
cis-1,2-DICHLOROETHYLENE	1.9	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02R	RAW
BROMODICHLOROMETHANE	0.5	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02E	EFF
CHLOROFORM	1.6	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 02E	EFF
CHLOROFORM	1.0	106	FIRE ROAD	01/21/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJD 06R	RAW
1,1,1-TRICHLOROETHANE	0.6	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 08R	RAW
CHLOROFORM	0.5	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 08R	RAW
cis-1,2-DICHLOROETHYLENE	0.9	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 08R	RAW
METHYL tert-BUTYL ETHER (MTBE)	0.5	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 08R	RAW
TETRACHLOROETHYLENE (PCE)	1.7	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 08R	RAW
TRICHLOROETHYLENE (TCE)	0.8	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 08R	RAW
BROMOFORM	0.9	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 09E	EFF
DIBROMOCHLOROMETHANE	1.2	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 09E	EFF
BROMODICHLOROMETHANE	0.5	109	GREENWICH DISTRICT	01/21/98	CONNECTICUT AMERICAN WATER CO	GREENWICH DISTRICT	CAW 09E	EFF

Chemical	Value	Code	Location	Date	System	Source	Unit	Type
4-METHYL-2-PENTANONE (MIBK)	5.5	103	DELAWARE VALLEY	01/23/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 42E	EFF
ETHYLBENZENE	1.3	103	DELAWARE VALLEY	01/23/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 42E	EFF
TOLUENE	3.0	103	DELAWARE VALLEY	01/23/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 42E	EFF
XYLENES (TOTAL)	8.6	103	DELAWARE VALLEY	01/23/98	NEW JERSEY AMERICAN WATER CO	DELAWARE VALLEY	NJD 42E	EFF
BROMODICHLOROMETHANE	4.0	106	FIRE ROAD	01/27/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 25E	EFF
CHLOROFORM	6.0	106	FIRE ROAD	01/27/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 25E	EFF
DIBROMOCHLOROMETHANE	1.8	106	FIRE ROAD	01/27/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 25E	EFF
BROMODICHLOROMETHANE	0.5	106	FIRE ROAD	01/27/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 60E	EFF
DIBROMOCHLOROMETHANE	0.5	106	FIRE ROAD	01/27/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 60E	EFF
CHLOROFORM	0.9	106	FIRE ROAD	01/27/98	NEW JERSEY AMERICAN WATER Co	FIRE ROAD	NJS 60E	EFF
BROMOFORM	3.8	701	CORONADO DISTRICT	02/03/98	CORONADO DISTRICT	CORONADO SUBLINE	DIST	
CHLOROFORM	6.6	701	CORONADO DISTRICT	02/03/98	CORONADO DISTRICT	CORONADO SUBLINE	DIST	
BROMODICHLOROMETHANE	11.4	701	CORONADO DISTRICT	02/03/98	CORONADO DISTRICT	CORONADO SUBLINE	DIST	
DIBROMOCHLOROMETHANE	12.6	701	CORONADO DISTRICT	02/03/98	CORONADO DISTRICT	CORONADO SUBLINE	DIST	
BROMODICHLOROMETHANE	24.6	701	CORONADO DISTRICT	02/03/98	CORONADO DISTRICT	MONTGOMERY TANK FEED	DIST	
BROMOFORM	4.6	701	CORONADO DISTRICT	02/03/98	CORONADO DISTRICT	MONTGOMERY TANK FEED	DIST	

CHLOROFORM	13.7	701	CORONADO DISTRICT	02/03/98	CORONADO DISTRICT	MONTGOMERY TANK FEED	DIST	
DIBROMOCHLOROMETHANE	20.9	701	CORONADO DISTRICT	02/03/98	CORONADO DISTRICT	MONTGOMERY TANK FEED	DIST	
1,2,3-TRICHLOROPROPANE	1.2	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 33R	RAW	
1,2-DICHLOROPROPANE	2.7	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 33R	RAW	
TRICHLOROETHYLENE (TCE)	0.5	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 33R	RAW	
1,1,1-TRICHLOROETHANE	0.5	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 35R	RAW	
TRICHLOROETHYLENE (TCE)	0.9	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 35R	RAW	
1,2,3-TRICHLOROPROPANE	0.5	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 37R	EFF	
1,2-DICHLOROPROPANE	1.3	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 37R	EFF	
TETRACHLOROETHYLENE (PCE)	7.3	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 05R	RAW	
1,1-DICHLOROETHANE	0.5	103	DELAWARE VALLEY	02/03/98	DELAWARE VALLEY	NJD 23E	EFF	
CHLOROFORM	0.9	105	LAKEWOOD	02/10/98	NEW JERSEY AMERICAN WATER CO	LAKEWOOD	NJL 42R	RAW
CHLOROFORM	0.6	105	LAKEWOOD	02/10/98	NEW JERSEY AMERICAN WATER CO	LAKEWOOD	NJL 43R	RAW
BROMODICHLOROMETHANE	8.3	102	MONMOUTH	03/11/98	MONMOUTH	EFF		
CHLOROFORM	26.7	102	MONMOUTH	03/11/98	MONMOUTH	EFF		
DIBROMOCHLOROMETHANE	1.2	102	MONMOUTH	03/11/98	MONMOUTH	EFF		

BROMODICHL OROMETHAN E	2.0	102	MONMOUTH	03/11/98	MONMOUTH	RAW
CHLOROFOR M	7.1	102	MONMOUTH	03/11/98	MONMOUTH	RAW
CHLOROFOR M	0.5	105	LAKEWOOD	03/11/98	LAKEWOOD	RAW